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THE

IRON AND STEEL INSTITUTE

CARNEGIE SCHOLARSHIP MEMOIRS

Vol. XII.

EDITED BY

GEORGE C. LLOYD

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LONDON
E. & F. N. SPON, LIMITED, 57, HAYMARKET
NEW YORK: SPON & CHAMBERLAIN, 123, LIBERTY STREET
SOLD ALSO AT THE OFFICES OF THE INSTITUTE
28, VICTORIA STREET, LONDON, S.W.
1923

TS
300
I733
v. 12

Printed in England at THE BALLANTYNE PRESS
SPOTTISWOODE, BALLANTYNE & CO. LTD.
Colchester, London & Eton

CONTENTS

PAGE

SECOND REPORT ON THE RELATIVE CORRODIBILITIES OF VARIOUS COMMERCIAL FORMS OF IRON AND STEEL. By Dr. J. NEWTON FRIEND (Birmingham) 1

Metals employed 2
Field tests 2
Chemical analyses of the metals 3
Mechanical properties 4
Laboratory tests 6
Corrosion in tap water 8
Corrosion in salt water 9
Influence of strain upon the corrosion of iron 12
Relative corrosion of longitudinal and transverse sections of mild steel 15
Relative corrodibilities of wrought iron, carbon steels, and cast iron 16
Influence of carbon on corrosion in neutral media . . . 17
Influence of manganese 19
Influence of copper 21
Influence of nickel and chromium 22

DETERMINATION OF THE CORRECTIONS TO OPTICAL PYROMETER READINGS TAKEN DURING STEEL MAKING AND CASTING. By Dr. J. NEILL GREENWOOD (Sheffield) . . . 27

Summary of report 27
Scheme of investigation 30
Difficulties met with in obtaining true temperatures . . . 32
Calibration of the pyrometer 35
Temperatures of cool dead soft steel casts 36
Determination of the departure from perfect radiator conditions in the open-hearth 40
Effect of flames on temperatures in furnace 42
Are the temperatures obtained of small diameter streams low ? . 49
Temperature observations on small streams 50
Consideration of previously published results 52
Application of results obtained 55

APPENDIX I.

Comparison of temperatures taken in furnace under different conditions 62

PAGE

Appendix II.

Comparison of last temperatures taken in furnace before tapping with those taken during tapping 69

AN INVESTIGATION OF THE BEHAVIOUR OF CERTAIN STEELS UNDER IMPACT AT DIFFERENT TEMPERATURES. By Dr. F. C. Langenberg (Watertown Arsenal, U.S.A.) 75

Material investigated 78
Methods of testing 79
Stress strain curves of tensile specimens 82
Impact testing machine used 86
Methods of obtaining the desired temperatures 87
Dimensions of test specimens 90
Discussion of results 91

Correspondence :

L. Aitchison 109
R. H. Greaves 110

THE LOW APPARENT ELASTIC LIMIT OF QUENCHED OR WORK-HARDENED STEELS. By Dr. Leslie Aitchison (Birmingham) 113

Introduction 113
Experimental materials 120
Mechanical tests 121
Heat treatment of specimens 121
Limit of proportionality of heat-treated specimens . . . 126
Proof stress in tension of heat-treated specimens . . . 140
Effect of prolonged tempering at a low temperature upon the limit of proportionality of an air-hardened nickel-chromium steel . 146
Tests on steel strip 152
Tests on normalised plain carbon steel 153
Fatigue tests 155
Magnetic tests 170
Magnetic values obtained after different heat treatments . . 176
Changes in permeability produced by various treatments . . 176
Constitutional tests 185
Corrosion tests. 186
Conclusions 193

IRON IN ANTIQUITY. By Dr. J. Newton Friend (Birmingham) . 219

Introduction 219
The age of stone 221
Native metals 223
The age of metals 227
Transition periods 231
Iron and the language 234

PAGE
Iron as treasure 237
Localities and numbers of currency bars found 239
Iron in Europe 247
  Iron and Homer 247
  Iron and Herodotus 255
  Iron and Crete 257
  Iron in Austria and Switzerland 259
  Iron in Italy 261
  Iron and the Romans 261
  Iron in Britain 265
  Iron and the Vikings 267
Iron in India 268
Iron in Ceylon 274
Iron in Egypt 277
Iron in Palestine 280
Iron in Mesopotamia 284
Iron in Africa 287
Iron in China and Japan 287
Iron in Mexico and Peru 288
Finis 290

EFFECT OF COLD-WORKING ON THE ELASTIC PROPERTIES OF STEEL. By J. A. Van den Broek.

  Mr. Van den Broek's reply to discussion and correspondence on his paper (*C.S.M.*, vol. ix., 1918) 291

LIST OF PLATES.

Plate I. Photographs illustrating Dr. Friend's report on the Relative Corrodibilities of Iron and Steel . . *To face p.* 16
Sheet with Tables V. and VI. in Dr. Langenberg's report. . . . . . . ,, 96
Plates II. to X. Photomicrographs and photographs illustrating Dr. Langenberg's report *Between pp.* 106–107
XI. to XII. Photomicrographs illustrating Dr. Aitchison's report . . . . ,, 192–193
XIII. to XVI. Photographs illustrating Dr. Friend's Memoir, Iron in Antiquity . . ,, 288–289

Iron and Steel Institute.

SECOND REPORT ON THE RELATIVE CORRODIBILITIES OF VARIOUS COMMERCIAL FORMS OF IRON AND STEEL.

By J. NEWTON FRIEND, D.Sc., Ph.D., F.I.C. (Birmingham).

In 1922 a Preliminary Report was published giving the results of a series of laboratory tests on the relative corrodibilities of various forms of iron and steel under different conditions. These experiments have now been extended as detailed hereunder.

Scope of the Research.

The aims of the present research are four in number, namely :

1. To determine by means of "field tests" the relative corrodibilities of various commercial forms of iron and steel under varying conditions of exposure.
2. To determine in a similar manner the relative corrodibilities of the more important non-ferrous metals and some of their alloys.
3. To carry out simultaneously several series of laboratory tests to ascertain whether or not they yield results comparable with the field tests, and hence to obtain an indication as to their value in practice.
4. To study the influence of chemical composition, micrographic structure, and other properties upon corrodibility.

To this end considerable supplies of various metals of commercial importance have been acquired, amounting in all to forty different kinds of iron and steel, including some of the more common types of special steel, and seventeen non-ferrous metals and alloys. Some of these have been obtained by purchase, the cost having been defrayed by a grant from the Carnegie Scholarship Fund of this Institute. The author desires to take this opportunity of thanking the committee for their generous support, which has made possible the carrying out of this research. The majority of the ferrous metals, and the whole of the non-ferrous metals and alloys, have been generously given to the author by various firms, whose kindness is here gratefully acknowledged. All the metals are in the form of round bars, $1\frac{1}{4}$ inch in diameter, and have been cut into 2-foot lengths.

The Metals Employed.

These comprise

1 commercially pure iron.
12 wrought irons.
9 carbon steels.
12 special steels.
3 cast irons.
1 metallic nickel.
16 non-ferrous metals (other than nickel).

Bars of all the metals are undergoing corrosion in the field tests, but laboratory tests with non-ferrous metals other than nickel have not as yet been arranged. The chemical analyses and mechanical properties of the ferrous metals are given in the accompanying tables (see Tables I. and II.). From a consideration of these it will be evident that the metals cover a wide range and may be regarded as reasonably representative of the various kinds of steel used in modern practice.

Quite apart from any connection with corrodibility, these data are interesting as having been obtained with a wide range of commercial steels as manufactured for industry, and not, as in so many cases, specially prepared for research purposes.

Field Tests.

The metal bars are weighed and placed in large wooden frames specially constructed for the purpose, as shown in Figs. 1 and 2. These consist of two long battens supported by four stout laths, two at each end, securely bolted by four long bolts. The frames hold from fifty to fifty-four bars, placed 3 inches apart from centre to centre, the total length of the frames measuring some 14 feet. The long battens, which are 4 inches square in cross

TABLE I.—*Chemical Analyses of the Metals.*

Identification Mark.	Metal.	C.	Si.	S.	P.	Mn.	Ni.	Cr.	Cu.	W.
A1	Commercially pure iron	0·025	0·15	0·014	0·031	0·05	...	...	0·01	...
EB	Wrought irons	0·060	0·12	0·030	0·27	0·10	...	...	0·06	...
EBB		0·035	0·10	0·024	0·27	0·06	...	...	0·04	...
EBC		0·029	0·12	0·038	0·28	0·07	...	...	0·04	...
EC		0·043	0·14	0·029	0·28	0·14	...	...	0·05	...
HA		0·025	0·10	0·044	0·23	0·16	...	...	0·06	...
HB		0·034	0·09	0·041	0·20	0·13	...	...	0·07	...
HBB		0·014	0·09	0·036	0·21	0·19	...	...	0·06	...
HBBB		0·036	0·10	0·038	0·21	0·13	...	...	0·08	...
HC		0·042	0·10	0·028	0·18	0·10	...	...	0·06	...
L		0·034	0·11	0·017	0·14	0·03	...	...	0·04	...
RBB		0·011	0·14	0·020	0·25	0·07	...	...	0·09	...
RBBB		0·144	0·03	0·023	0·55	0·04	...	...	0·05	...
DU	Carbon steels.	0·220	0·024	0·076	0·054	0·453	...	...	...	...
DV		0·116	0·028	0·084	0·048	0·455	...	...	...	...
H1		0·11	0·004	0·033	0·058	0·33	...	...	0·01	...
H2		0·14	0·016	0·052	0·073	0·35	...	...	0·02	...
H3		0·15	0·028	0·062	0·023	0·47	...	...	0·03	...
RM		0·20	0·005	0·055	0·061	0·69	...	...	0·04	...
RS		0·05	0·005	0·043	0·122	0·41	...	...	0·03	...
WH		0·32	0·132	0·046	0·055	0·64	...	...	...	...
WM		0·13	0·121	0·062	0·044	0·55	...	...	...	...
HCU	*Special Steels* Cupriferous.	0·13	0·01	0·025	0·036	0·44	nil	nil	0·15	...
HS	"Stainless"	0·23	0·61	0·057	0·019	0·20	nil	13·40	...	...
FS	Do. .	0·42	0·31	0·019	0·037	0·43	nil	11·73	nil	...
FS2	Do. .	0·42	0·31	0·019	0·037	0·43	nil	11·73	nil	...
S19	Do. .	0·37	0·008	0·083	0·036	0·17	0·54	12·75	0·03	...
K1	Nickel-chromes	0·37	0·20	0·051	0·051	0·54	3·66	1·05	0·02	...
S2		0·28	0·16	0·036	0·041	0·40	3·53	0·67	0·01	...
S8		0·35	0·22	0·025	0·020	0·42	3·52	0·05	0·01	...
S10		0·34	0·12	0·037	0·021	0·52	2·88	0·10	0·02	...
S12		0·37	0·11	0·032	0·044	0·58	3·44	0·66	0·02	0·39
S16		0·15	0·22	0·045	0·043	0·40	1·89	0·84	0·01	...
S17		0·11	0·10	0·031	0·032	0·36	5·80	0·14	0·02	...
CA	Cast irons	C[1] 0·51 F[2] 2·64	1·62	0·077	0·87	0·50	...	...	<0·01	...
CC		C 0·20 F 2·99	2·72	0·110	1·32	0·51	...	...	<0·01	...
W1		C 0·56 F 2·96	1·50	0·096	0·97	0·88	...	...	...	...

[1] C = Combined.

[2] F = Free or graphitic.

TABLE II.—*Mechanical Properties.*

Identification Mark.	Metal.	Yield Point. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elongation on 18 Cms. Per Cent.	Reduction of Area. Per Cent.	Ball Hardness No.
A1	Commercially pure iron	19·68	25·06	28·90	43·2	126
EB	Wrought irons.	21·30	25·34	30·00	39·6	134
EBB		17·84	24·34	23·90	35·9	118
EBC		19·08	23·96	23·90	43·2	121
EC		19·22	26·00	29·40	62·4	128
HA		17·68	24·26	30·50	47·2	118
HB		17·40	24·34	22·50	35·0	128
HBB		18·66	23·56	30·00	47·2	116
HBBB		18·16	23·62	33·00	47·2	112
HC		16·14	23·54	20·30	30·6	126
L		18·12	23·94	28·30	50·0	107
RBB		19·86	24·92	31·40	43·2	126
RBBB		18·00	25·76	28·90	54·2	126
	Carbon Steels.					
DU	C 0·220 . .	19·87	28·53	29·70	59·8	116
DV	C 0·116 . .	15·44	20·48	36·00	72·8	105
H1	C 0·11 . .	17·71	25·35	32·20	65·4	92
H2	C 0·14 . .	18·64	28·06	26·10	54·2	107
H3	C 0·15 . .	17·14	26·70	30·20	63·8	105
RM	C 0·20 . .	19·67	30·66	28·00	59·8	118
RS	C 0·05 . .	20·32	27·26	34·20	68·2	103
WH	C 0·32 . .	22·35	38·66	23·30	52·0	153
WM	C 0·13 . .	18·92	28·10	30·80	63·8	124
	Special Steels.					
HCU	Cu 0·15 . .	22·47	27·86	31·10	64·8	124
HS	" Stainless " .	45·71	54·12	9·75	50·0	387
FS	" .	59·65	60·62	8·9	46·2	286
FS2	" .	...	...	...	...	477
S19	" .	...	...	...	...	...
K1	Ni 3·66 Cr 1·05	53·90	60·16	11·50	58·0	262
S2	Ni 3·53 Cr 0·67	63·90	66·49	8·35	56·6	286
S8	Ni 3·52 Cr 0·05	36·38	67·40	16·40	63·8	207
S10	Ni 2·88 Cr 0·10	29·23	42·38	22·20	54·2	183
S12	Ni 3·44 Cr 0·66 W 0·39	...	...	...	...	351
S16	Ni 1·89 Cr 0·84	24·24	36·50	22·50	66·0	156
S17	Ni 5·80 Cr 0·14	27·13	36·97	19·70	63·8	166
CA	Cast irons .	...	11·27	...	...	212
CC		...	13·69	...	...	241
W1		...	16·42	...	...	146

section, are bored each with as many holes of 1¼-inch diameter as the frame is to contain bars, one batten—the upper one in

Fig. 1—being bored completely through, the other to a depth of 1 inch only. A little putty is placed in these lower holes, the bars are slipped through the upper batten, and their ends pressed down into the putty in the lower holes. The upper holes are now partially filled with putty, wooden plugs hammered in to fill them, and laths nailed along the top to prevent the plugs from working out. The bars are thus securely fixed into the frame, the putty serving to guard the ends of the bars from attack.

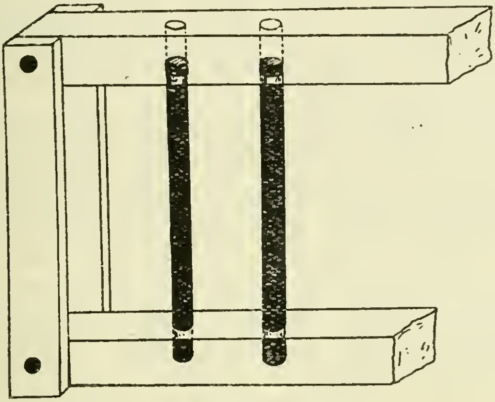

Fig. 1.

One such frame has been fixed on the roof of the Birmingham Municipal Technical School; another is in process of erection in the sea at Weston-super-Mare.[1] Other similar frames are being prepared, but arrangements for these are not yet quite complete. The exposures will be continued for several years, at the end of which time the bars will be removed, cleaned, and weighed, their loss through corrosion being thereby determined. Depth of pitting, change in composition—more particularly in the case of alloys—and any other points of interest will be duly recorded. The data thus obtained should enable useful comparisons to be drawn between various ferrous and non-ferrous metals from the point of view of their corrodibilities.

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[1] April 1923. It has now been completed (May 1923), and the author's best thanks are due to Mr. McKaig, A.M.Inst.C.E., of Weston, for his kind assistance.

LABORATORY TESTS.

Laboratory tests have, up to the present, been carried out with both small and large specimens of the various ferrous metals and with small specimens only of nickel.

Small Specimens.—These consisted of thin transverse slices of the bars, measuring 1·12 inch in diameter, approximately 0·2 inch in thickness, and weighing about 20 grammes. Mill-scale was removed by filing on the lathe prior to slicing, and polishing with emery paper.

The stainless steel bars had already been supplied in a polished condition by the manufacturers, with the exception of S19, and therefore required no treatment other than slicing. Each disc was carefully measured, and its superficial area calculated.[1] After weighing it was laid on a piece of paraffin wax and exposed to corrosion. At the end of a suitable period the discs were removed, cleaned with a brush in flowing water, gently scraped free from closely adherent oxide, dried and weighed.

Large Specimens.—These consisted of sections of the bars some 3 inches in length, of similar diameter to the small specimens and weighing approximately 375 grammes. All the specimens were treated in a precisely similar manner to the preceding.

Four different types of test have been carried out, namely :

1. Continuous immersion in Birmingham tap-water in a large galvanised iron tank, fitted with a perforated false bottom which was covered with paraffin wax to prevent galvanic action. This is the nearest laboratory analogy to the conditions experienced in the case of steel pipes submerged in spring or river water.
2. Alternate wet and dry in a tank which filled with tap-water and emptied itself about every two hours—a process that closely corresponds to the action of the weather in our uncertain climate, as well as to the conditions experienced by the water-line portions of struc-

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[1] It has been assumed in this investigation that the rate of corrosion is directly proportional to the area exposed. This is correct, within the error of experiment, when the differences in area are small.

tures half in and half out of rivers or canals, as, for example, canal lock gates, the water-line of river steamers, and so on.

3. Continuous immersion in artificial sea-water—3 per cent. sodium chloride solution—in a large galvanised iron tank measuring 6 × 3 feet in area and $1\frac{1}{2}$ feet in depth, fitted with a false bottom and holding approximately half a ton of water.
4. Continuous immersion in 20 litres of 0·5 per cent. sulphuric acid. Duration, twenty-two hours. This is a fairly dilute solution, for in nature one rarely has to deal with concentrated acids. The acid waters of mines, for example, are really very dilute in most cases, and it did not seem to the author that a study of the action of more concentrated acid would be of any practical value.

Results for each of these with small specimens have already been detailed in the previous report. In Tables III. and IV. are given the results obtained by methods (1) and (3) with small and large specimens after one year's exposure.

Combining the foregoing results with those detailed in the Report for 1922, to which reference has already been made, and giving equal weight to each series, Table V., on pp. 10–11, may be compiled.

One point of interest was to determine whether or not the small specimens would manifest the same relative rates of corrosion amongst themselves as the larger ones. In the former case the areas exposed to corrosion are mainly transverse sections, whereas in the latter specimens the corroded areas are mainly longitudinal. In the steels and cast irons the macrostructures of these areas are not so widely different, but a glance at the macrosections in Fig. 3 (Plate I.) indicates a very marked difference in the case of the wrought irons. These photographs were taken after the discs had been immersed in dilute sulphuric acid (0·5 per cent.) for twenty-two hours. It seems reasonable to expect that a transverse face of EB, for example, will corrode at a different rate from the more homogeneous outer longitudinal layer.

There is no marked evidence of this, however, in the

TABLE III.—*Corrosion in Tap-Water.*

Duration, one year. Mean temperature, 10° C.

Identification Mark.	Metal.	Large Specimens.			Small Specimens.		
		Loss.	Loss per 1000 Sq. Ins.	Mean.	Loss.	Loss per 1000 Sq. Ins.	Mean.
A1	Commercially pure iron	2·56	217	217	0·430	256	256
EB	Wrought irons	2·61	221	227	0·399	254	241
EBB		2·65	226		0·373	241	
EBC		2·64	227		0·374	241	
EC		2·72	237		0·386	232	
HA		2·30	187		0·416	246	
HB		2·60	220		0·372	236	
HBB		2·63	224		0·401	242	
HBBB		2·57	215		0·379	229	
HC		2·51	221		0·414	246	
L		2·67	225		0·392	266	
RBB		2·51	221		0·329	216	
RBBB		2·38	206		0·427	237	
	Carbon Steels.						
DU	C 0·220	2·59	224	225	0·398	257	252
DV	C 0·116	2·50	221		0·386	256	
H1	C 0·11	2·52	219		0·399	251	
H2	C 0·14	2·67	230		0·414	238	
H3	C 0·15	2·60	227		0·425	253	
RM	C 0·20	2·69	225		0·414	254	
RS	C 0·05	2·63	226		0·429	267	
WH	C 0·32	2·72	234		0·422	249	
WM	C 0·13	2·57	221		0·420	243	
	Special Steels.						
HCU	Cupriferous, Cu 0·15	2·62	226	226	0·359	238	238
HS	" Stainless "	0·21	18	13	0·007	4	15
FS	,,	0·14	12		...	...	
FS2	,,	0·20	17		...	...	
S19	,,	0·06	5		0·044	25	
K1	Ni 3·66 Cr 1·05	2·12	180	193	0·356	208	216
S2	Ni 3·53 Cr 0·67	2·21	194		0·377	199	
S8	Ni 3·52 Cr 0·05	2·25	202		0·386	207	
S10	Ni 2·88 Cr 0·10	2·39	206		0·441	243	
S16	Ni 1·89 Cr 0·84	2·45	208		0·395	247	
S17	Ni 5·80 Cr 0·14	1·91	167		0·329	188	
S12	Ni 3·44 Cr 0·66 W 0·39	2·26	203		...	...	
CA	Cast irons	2·79	236	229	0·371	233	231
CC		2·73	229		0·399	227	
W1		2·65	221		0·422	233	
Ni	Nickel	...	...		0·005	3	3

All weighings are expressed in grammes.

TABLE IV.—*Corrosion in Salt Water.*

Duration, one year. Mean temperature, 10° C.

Identification Mark.	Metal.	Large Specimens.			Small Specimens.		
		Loss.	Loss per 1000 Sq. Ins.	Mean.	Loss.	Loss per 1000 Sq. Ins.	Mean.
A1	Commercially pure iron	0·97	82	82	0·280	174	174
EB	Wrought irons .	1·05	89	166	0·290	173	162
EBB		2·18	190		0·302	185	
EBC		0·96	84		0·329	190	
EC		2·13	186		0·298	167	
HA		2·32	197		0·303	180	
HB		1·93	166		0·144	91	
HBB		2·29	194		0·333	191	
HBBB		1·21	103		0·275	170	
HC		2·46	211		0·313	176	
L		2·17	189		0·254	170	
RBB		2·09	187		0·258	177	
RBBB		2·25	197		0·137	75	
	Carbon Steels.						
DU	C 0·220 . .	2·39	207	203	0·306	187	177
DV	C 0·116 . .	2·24	199		0·296	176	
H1	C 0·11 . .	2·42	208		0·292	189	
H2	C 0·14 . .	2·26	193		0·331	180	
H3	C 0·15 . .	2·38	208		0·163	103	
RM	C 0·20 . .	2·19	185		0·322	192	
RS	C 0·05 . .	2·43	206		0·270	178	
WH	C 0·32 . .	2·44	210		0·362	207	
WM	C 0·13 . .	2·41	209		0·314	184	
	Special Steels.						
HCU	Cu 0·15 . .	1·99	171	171	0·115	170	70
HS	"Stainless" .	0·11	10	19	0·025	14	25
FS	,, .	0·15	13		...	...	
FS2	,, .	0·11	9		...	...	
S19	,, .	0·49	42		0·065	35	
K1	Ni 3·66 Cr 1·05	2·23	198	183	0·284	172	167
S2	Ni 3·53 Cr 0·67	1·97	174		0·315	165	
S8	Ni 3·52 Cr 0·05	1·91	167		0·290	161	
S10	Ni 2·88 Cr 0·10	2·18	189		0·350	191	
S16	Ni 1·89 Cr 0·84	2·37	203		0·259	162	
S17	Ni 5·80 Cr 0·14	1·88	164		0·261	152	
S12	Ni 3·44 Cr 0·66 W 0·39	2·19	191	191	...	...	
CA	Cast irons .	2·00	170	165	0·327	186	190
CC		1·87	159		0·324	180	
W1		...	...		0·399	204	
Ni	Nickel . .	...	...		0·015	8	8

All weighings are expressed in grammes.

TABLE V.—*Summary of Results.*

The data refer to losses in weight, expressed in grammes, per 1000 square inches of surface.

Identification Mark.	Metal.	Continuous Tap-Water.					Alternate Wet and Dry.		Continuous Salt Water.					H_2SO_4. 0·5 per Cent.	
		Small Specimens. Four Months.	Small Specimens. One Year.	Large Specimens. One Year.	Total.	Mean.	Small Speci mens. Four Months.	Mean.	Small Specimens. Four Months.	Small Specimens. One Year.	Large Specimens. One Year.	Total.	Mean.	Small Specimens.	Mean.
A1	Commercially pure iron	98	256	217	569	569	...		80	174	82	336	336	76	76
EB	Wrought irons	105	254	221	580	564	193	194	84	173	89	346	414	703	461
EBB		102	241	226	569		196		80	185	190	455		745	
EBC		104	241	227	572		177		88	190	84	362		673	
EC		108	232	237	577		184		82	167	186	435		633	
HA		107	246	187	540		180		92	180	197	469		456	
HB		105	236	220	561		197		86	91	166	343		379	
HBB		100	242	224	566		197		85	191	194	470		438	
HBBB		107	229	215	551		200		88	170	103	361		445	
HC		98	246	221	565		201		86	176	211	473		324	
L		106	266	225	597		203		84	170	189	443		304	
RBB		102	216	221	539		193		82	177	187	446		239	
RBBB		108	237	206	551		206		91	75	197	363		198	
	Carbon Steels.														
DU	C 0·220	105	257	224	586	580	219	203	88	187	207	482	468	232	231
DV	C 0·116	102	256	221	579		204		87	176	199	462		127	
H1	C 0·11	101	251	219	571		190		88	189	208	485		131	
H2	C 0·14	102	238	230	570		202		89	180	193	462		164	
H3	C 0·15	99	253	227	579		208		86	103	208	397		234	
RM	C 0·20	110	254	225	589		192		91	192	185	468		217	
RS	C 0·05	94	267	226	587		191		82	178	206	466		497	
WH	C 0·32	105	249	234	588		211		96	207	210	513		352	
WM	C 0·13	107	243	221	571		207		84	184	209	477		127	

TABLE V. (*continued*).

Identification Mark.	Metal.	Continuous Tap-Water.					Alternate Wet and Dry.		Continuous Salt Water.					H_2SO_4. 0·5 per Cent.	
		Small Specimens. Four Months.	Small Specimens. One Year.	Large Specimens. One Year.	Total.	Mean.	Small Specimens. Four Months.	Mean.	Small Specimens. Four Months.	Small Specimens. One Year.	Large Specimens. One Year.	Total.	Mean.	Small Specimens.	Mean.
	Special Steels.														
HCU	Cu 0·15	101	238	226	565	565	212	212	79	170	171	420	420	73	73
HS	" Stainless "	6	4	18	28		...		41	14	10	65		183	
FS	"	...	...	12	12		...		...	...	13	13		...	
FS2	"	...	...	17	17		...		...	...	9	9		...	
S19	"	15	25	5	45		23		35	35	42	112		270	
K1	Ni 3·66 Cr 1·05	100	208	180	488	498	159	165	94	172	198	464	437	127	127
S2	Ni 3·53 Cr 0·51	94	199	194	487		143		86	165	174	425		88	
S8	Ni 3·52 Cr 0·05	94	207	202	503		169		84	161	167	412		69	
S10	Ni 2·88 Cr 0·10	101	243	206	550		202		103	191	189	483		169	
S16	Ni 1·89 Cr 0·84	105	247	208	510		159		78	162	203	443		269	
S17	Ni 5·80 Cr 0·14	93	188	167	448		157		80	152	164	396		43	
S12	Ni 3·44 Cr 0·66 W 0·39	...	...	203	203		...		...	...	191	...		...	
CA	Cast irons	115	233	236	584	570	206	201	86	186	170	442	438	1355	1326
CC		110	227	229	566		210		94	180	159	433		1343	
W1		105	233	221	559		188		79	204	...	...		1279	
Ni	Nickel	5	3	...	...		6		23	8	...	...		3	

experimental results as detailed in Tables III. and IV. for the wrought-iron specimens.

This is somewhat surprising. Probably, however, the wide individual variations in the salt solution tests are attributable to this cause, for in such solution galvanic activity due to irregularity in composition is accentuated above that in tap-water, which is less electrolytically active.

Such variations as occur, for example, between the (small and large) specimens EBC and RBBB in Table IV. on the one hand, find no parallel amongst the more homogeneous carbon steels.

Again, it is to be anticipated that when the larger specimens have been heavily corroded, so that the outer layer has oxidised away, the inner core will disintegrate at a different rate. It is intended, therefore, to carry out these corrosion tests to destruction in order to obtain information on this point.

THE INFLUENCE OF STRAIN UPON THE CORROSION OF IRON.

This is a subject which has not been investigated as thoroughly as its importance would warrant. Although many determinations have been made of the potential differences between strained and unstrained ferrous metals,[1] and also of the rate of solution of these metals in dilute acids,[2] the only published data on the influence of strain on corrosion in neutral media appear to be those of the present author, given in the Carnegie Scholarship Memoir of this Institute in 1922. These researches have now been extended to include exposures each of one year's duration in tap-water and in 3 per cent. salt water (artificial sea-water) respectively.

The steels used in this research were obtained as cylindrical bars, 1 inch in diameter, and in four grades, namely A, B, C, D, which differed mainly in their carbon content. Their composition was as follows :

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[1] Andrews, *Minutes of Proceedings of the Institution of Civil Engineers*, 1894, vol. cxviii. p. 356; Walker and Dill, *Transactions of the American Electrochemical Society*, 1907, vol. xi. p. 153; Hambuechen, *Bulletin, University of Wisconsin, Engineering Series* 8, 1900; Burgess, *Transactions of the American Electrochemical Society*, 1908, vol. xiii. p. 17; Richards and Behr, *Publications of the Carnegie Institute, Washington*, 1906; *Zeitschrift für physikalische Chemie*, 1907, vol. lviii. p. 301.

[2] Heyn and Bauer, *Journal of the Iron and Steel Institute*, 1909, No. I. p. 109.

TABLE VI.—*Analysis of the Steels.*

	A.	B.	C.	D.
Carbon	0·174	0·467	0·920	1·350
Silicon	0·132	0·150	0·076	0·092
Manganese	0·600	0·480	0·706	0·286
Sulphur . . .	0·033	0·051	0·024	0·024
Phosphorus . . .	0·033	0·044	0·030	0·027

From each bar three pieces were cut (denoted in the sequel as A, AA, AAA ; B, BB, BBB, &c.), 9 inches long, and ground into test-bars. Small marks were made along the length of each bar exactly 1 inch apart, and the steels were then placed in a tensile testing machine and broken.[1] The total and sectional elongations were noted, the bars turned to a uniform diameter, sawn at the marks into small cylindrical pieces, approximately 0·8 inch in height, and 0·6 inch in diameter. The exact size of each test-piece was measured and its superficial area exposed to corrosion was calculated.[2] It is assumed that the portion of the metal under the grips was not appreciably strained.

The experiments in acid solution have not been repeated, for all investigators agree that the rate of solution of ferrous metals in these circumstances is greatly enhanced by strain.

The experiments carried out in tap-water and 3 per cent. salt solution were conducted in a precisely similar manner to the previous ones, and the results, together with those of the earlier ones, are grouped together in Tables VII. and VIII. The data under *relative corrosion* are in every case calculated relatively to the unstrained bar of similar chemical composition, the loss in weight of which is taken as 100.

It is remarkable that the influence of strain and overstrain

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[1] Full details are given in the *Carnegie Scholarship Memoirs*, 1922, vol. xi. Part III.

[2] As the differences in the superficial areas were very small, amounting on the average to about 2 per cent., the extremes being about 3·5 per cent. either way from the mean, it is assumed that the rates of corrosion are directly proportional to the areas. It is only when the areas vary by large amounts that this proportionality becomes appreciably incorrect.

Table VII.—*Corrosion of Strained Steels in Neutral Media.*

All losses in weight are expressed in grammes per 1000 square inches of area exposed.

Test-Piece.	Carbon per Cent.	Elongation per Cent.	Alternate Wet and Dry. 6 Months.	Continuous Immersion in Tap-Water. 4 Months.	Continuous Immersion in 3 per Cent. NaCl Solution. One Year.	Relative Corrosion.
A 0	0·174	0·0	308	107	300	100
2		10·9	323	114	310	104
1		14·1	318	112	302	103
3		18·7	294	118	303	100
B 0	0·467	0·0	297	122	325	100
2		9·4	298	122	314	99
3		12·5	309	126	322	101
C 0	0·920	0·0	322	126	275	100
1		3·1	308	127	325	105
3		4·7	333	129	314	106
4		10·9	307	129	313	104
D 0	1·350	0·0	353	126	293	100
3		3·1	364	134	285	101

Table VIII.—*Corrosion of Strained Steels in Neutral Media.*

All losses in weight are expressed in grammes per 1000 square inches of area exposed.

Test-Piece.	Carbon per Cent.	Elongation per Cent.	Continuous Immersion in Tap-Water. 6½ Months.	Continuous Immersion in 3 per Cent. NaCl Solution. 8 Months.	Alternate Wet and Dry. One Year.	Relative Corrosion.
AA 0	0·174	0·0	174	231	579	100
2		17·2	177	233	574	100
3		34·4	170	232	560	98
BB 0	0·467	0·0	181	245	645	100
2		9·4	181	243	545	91
3		10·9	181	253	546	92
4		29·7	180	245	599	96
CC 0	0·920	0·0	190	256	549	100
3		9·4	183	256	564	100
DD 0	0·351	0·0	180	223	361	100
4		1·6	186	226	429	110

on the rate of corrosion in neutral media should be so small. As pointed out in the previous Memoir, however, this highly interesting result must not be taken to mean that a strained steel structure is no more likely to corrode than one that is unstrained. It must be remembered that the specimens used in this research were not only uniformly strained throughout —a condition unlikely to occur in practice—but they were galvanically isolated during the tests by resting on blocks of paraffin wax, so that electrical contact was impossible. Now in practice if a metal be strained at any point, it is the area of contact between the strained and unstrained (or less strained) portions that suffers severely, one part acting anodically to the other during part or the whole of the exposure. It will be clear that in these circumstances even reversal of polarity will not reduce the sum total of corrosion; indeed it may accelerate corrosion by drawing it to fresh areas which were at first cathodic and more or less immune.

TABLE IX.—*Relative Corrosion of Longitudinal and Transverse Sections of Mild Steel.*

Corroding Medium.	Duration.	Loss in Weight of Longitudinal Section. Grammes.	Loss in Weight of Transverse Section. Grammes.	Corrosion Factor of Transverse Specimen. (Longitudinal = 100.)
Complete immersion in tap-water .	3 months	1·205	1·275	106
Alternate wet and dry . . .	3 months	3·450	3·330	97
	1 year	7·486	7·776	104
Artificial sea-water . . .	1 year	2·495	2·607	104
	1 year	2·586	2·643	102
Dilute acid (0·1 per cent. H_2SO_4) .	8 days	1·130	1·090	97
Total	...	18·352	18·721	102

These results are in entire harmony with the preceding.

A few experiments have been carried out with longitudinal and transverse sections of mild steel which had not been annealed or normalised after rolling. It had the following chemical composition:

	Per Cent.
Carbon	0·08
Silicon	0·17
Manganese	0·36

The sections measured 4 × 1 inches in area, 0·1 inch in thickness, and weighed approximately 75 grammes. They were exposed to various corroding media, with the results shown in Table IX. (p. 15).

It is certainly curious that the influence of structure and strain upon the corrodibility of the metal should prove to be so small.

THE RELATIVE CORRODIBILITIES OF WROUGHT IRON, CARBON STEELS, AND CAST IRON.

This is a subject of perennial importance. Every new method of manufacturing and every modification of older methods may lead to variation in the finished product, resulting in a greater or less resistance to corrosion in service.

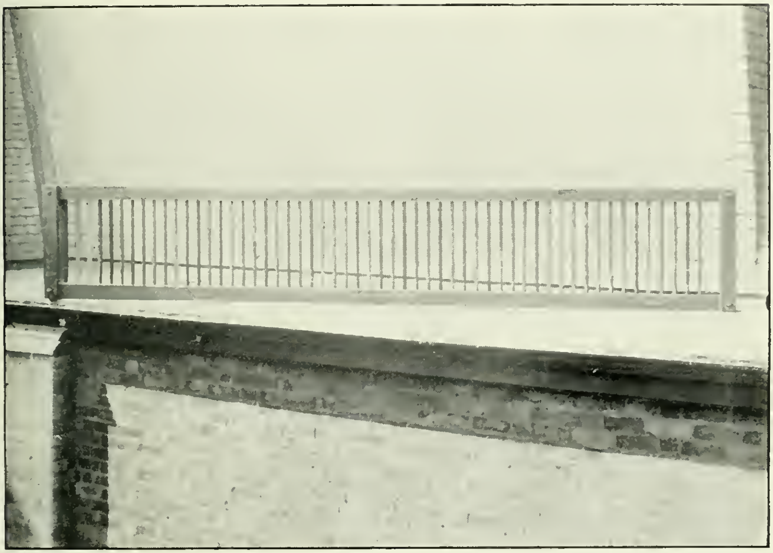
Consideration of the results in Table V., as briefly summarised in Table X., reveals the interesting and highly gratifying fact that the different varieties of wrought and cast irons and of carbon steels corrode in neutral media with remarkable uniformity.

TABLE X.—*Mean Losses in Weight of Wrought Irons, Cast Irons, and Carbon Steels.*

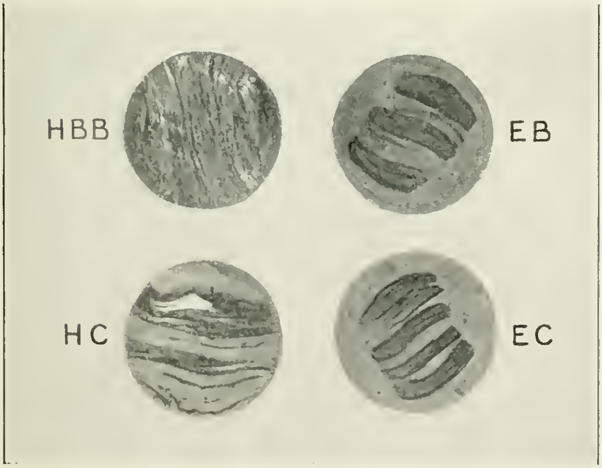
	Carbon per Cent.	Manganese per Cent.	Continuous Tap-Water.	Alternate Wet and Dry.	Continuous Salt Water.	Dilute H_2SO_4 per Cent.
Commercially pure iron	0·025	0·05	569	...	336	76
Mean of twelve wrought irons	0·04	0·10	564	194	414	461
Mean of nine carbon steels	0·16	0·48	580	203	468	231
Mean of three cast irons	Comb. 0·42 Free 2·86	0·63	570	201	438	1326

The "skins" had necessarily been removed from the cast irons, so that they were more susceptible to attack than usual. Nevertheless they are seen to have resisted corrosion quite as well as the steels in all the neutral tests. The wrought irons and carbon steels are remarkably similar in their powers of resistance, although in the salt-water tests the wrought irons show somewhat to advantage.

PLATE I.



Set of bars in frame on roof of Birmingham Municipal Technical School.



Transverse sections of wrought-iron bars after immersion in dilute acid (two-thirds natural size).

In the acid tests the wrought irons are less resistant than the steels, whilst the cast irons are even more seriously attacked.

The commercially pure iron is highly resistant to acid attack, resists salt water quite satisfactorily, and closely resembles the other forms of iron in its resistance to tap-water.

INFLUENCE OF CARBON ON CORROSION IN NEUTRAL MEDIA.

Attention has repeatedly been directed to the enhanced solubility of steels in dilute acid with increasing carbon content, until the eutectic point is reached, after which the solubility falls. It is interesting to compare the behaviour of the steels in neutral media, and to facilitate this the data for the unstrained specimens described in Table VI. are summarised in Table XI.

TABLE XI.—*Relative Corrodibilities of Unstrained Steels in Neutral Media.*

All losses in weight are expressed in grammes per 1000 square inches of area exposed.

Steel.	Carbon per Cent.	Manganese per Cent.	Continuous.		Continuous Immersion in Salt Water.		Alternate Wet and Dry.		Relative Corrosion.
			4 Months.	6½ Months.	8 Months.	1 Year.	6 Months.	1 Year.	
A	0·174	0·6	107	174	231	300	308	579	100
B	0·467	0·48	122	181	245	325	297	645	107
C	0·920	0·706	126	190	256	275	322	549	101
D	1·350	0·286	126	180	223	293	353	361	90

It will be seen that there is a tendency for the corrodibility to rise with the carbon content, but in the neighbourhood of the eutectic point there is a break in the curve, followed by a fall in corrosion. The effect is not very great, however. It is much more clearly seen in specimens of very low manganese content—of the order of 0·10 per cent.—as shown by Hadfield and Friend,[1] who point out that "just as in the experiments with the steels of 0·2 per cent. manganese content, a point of maximum corrosion is observed; but this always occurs with a smaller carbon content in the steels with 0·7 per cent. manganese." The manganese normally present in commercial steels, and probably also the usual variation in the proportions of some of the other minor constituents or impurities, tend to mask this influence unless the carbon content is very high.

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[1] Hadfield and Friend, *Journal of the Iron and Steel Institute*, 1916, No. I. p. 48.

This is clearly seen from the following summary (Table XII.), compiled from Table V., the corrodibilities being expressed relatively to that of the low carbon metal RS, which is in each case taken as 100.

TABLE XII.—*Effect of Small Variation in the Carbon Content of Steels on their Corrodibilities.*

Identification Mark.	Carbon per Cent.	Manganese per Cent.	Continuous Tap-Water.	Alternate Wet and Dry.	Continuous Salt Water.
RS	0·05	0·41	100	100	100
H1	0·11	0·33	97	100	104
DV	0·116	0·455	98	107	100
WM	0·13	0·55	97	109	104
H2	0·14	0·35	97	107	100
H3	0·15	0·47	98	109	83
RM	0·20	0·69	100	100	100
DU	0·22	0·453	100	115	110
WH	0·32	0·64	101	111	103

These results are in entire harmony with those of earlier investigations.[1] The data in Table XII. agree very closely with those of Hadfield and Friend, who studied, in a series of laboratory tests with small specimens, thirty-five varieties of steels of varying carbon and manganese contents, specially prepared for the research. The results given in Tables I., II., and III. of the Memoir referred to have been recalculated for purposes of direct comparison with Tables XI. and XII. of the present research, and are given in Table XIII.

Apart from small irregularities normally met with in the study of the corrosion of steel, it will be observed that these results show good general agreement with those in Tables XI. and XII.

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[1] See Chappell, *Chemical News*, 1911, vol. civ. p. 155; *Journal of the Iron and Steel Institute*, 1912, No. I. p. 270; Aitchison, *Transactions of the Faraday Society*, 1916, vol. xi. p. 212; Hadfield and Friend, *Journal of the Iron and Steel Institute*, 1916, No. I. p. 48.

TABLE XIII.—*Influence of Varying Carbon Content upon the Corrodibility of Steel* (*Hadfield and Friend*, 1916).

Carbon per Cent.	Manganese per Cent.	Continuous Tap-Water. 6 Months.	Alternate Wet and Dry. 1 Year.	Continuous Salt Water. 1 Year.
0·12	0·58	100	100	100
0·28	0·57	95	93	116
0·40	0·64	100	92	104
0·48	0·75	89	96	102
0·79	0·84	87	74	116
1·01	0·89	100	74	118
1·17	0·57	95	80	109

INFLUENCE OF MANGANESE.

For many years there has been a considerable amount of interest centred round the problem as to whether or not the presence of manganese in steel increases its liability to corrosion. The answer to this question was given in the affirmative by Berthier,[1] Siemens,[2] Snelus,[3] and more recently by Finkener,[4] and others.[5] In 1905 Cushman[6] gave the results of an extensive study of the causes leading to the corrosion of wire fence in America, and drew attention to the fact that the majority of the wires that had withstood corrosion reasonably well exhibited upon analysis a low manganese content, namely less than 0·2 per cent. On the other hand, the more corroded specimens generally contained some 0·5 per cent. of manganese. These results could not be regarded as conclusive evidence that alloyed manganese tends to increase the corrodibility of steel, for not only did the author omit to determine the sulphur content of the metals examined, but there were certain well-defined exceptions to his rule, for a few specimens of wire of 0·5 and even higher manganese content resisted corrosion quite satisfactorily.

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[1] See Mallet, *British Association Reports*, 1838, p. 265.

[2] Siemens, *Journal of the Iron and Steel Institute*, 1878, No. I. p. 425.

[3] Snelus, *ibid.*, 1881, No. I. p. 66.

[4] Finkener, *Mitteilungen aus der königlichen technischen Versuchsanstalt*, Berlin, 1897, vol. xv. p. 277.

[5] Other references to the influence of manganese are as follows: Heyn and Bauer, *Mitteilungen aus dem königlichen Materialprüfungsamt*, Berlin, 1908, vol. xxvi. p. 1; Aston and Burgess, *Eighth International Congress of Applied Chemistry*, Washington, September 1912; Desch and Whyte, *Journal of the West of Scotland Iron and Steel Institute*, 1914, vol. xxi. p. 176; Aitchison, *Transactions of the Faraday Society*, 1915, May and December.

[6] Cushman, *U.S. Department of Agriculture, Farmer's Bulletin*, No. 239, 1905.

Neglect of the sulphur content was an unfortunate oversight, for sulphur is well known to have a highly deleterious effect upon the corrodibility of iron; and if in the 0·5 manganese steels the sulphur content was proportionately high, it is easy to understand that the increased manganese, present mainly as sulphide, would greatly assist corrosion. In other words, the reputation of the manganese would be suffering by its bad companionship.

In 1916 the results of a comprehensive study of the influence of carbon and manganese upon the corrodibility of iron were published by Sir Robert Hadfield and the present author.[1] Thirty-five steels were examined, all of which were specially prepared for the research, small cylindrical specimens weighing about 18 grammes being employed in the tests. The data showed that by raising the manganese content of steels from about 0·10 per cent. to 0·5–0·9 per cent. there results:

(*a*) A very slightly increased corrosion in tap-water, sea-water, and in wet and dry tests with a carbon content up to about 0·4 to 0·5 per cent. From this point upwards the manganese, generally speaking, affords a slight protection, which is very decided in the wet and dry tests, but is not invariable in the sea-water tests.

(*b*) An enormously increased corrosion in dilute sulphuric acid. This is particularly important, since in commercial steels the manganese content frequently ranges from 0·2 to 0·7 per cent., and it is evident that the latter are absolutely unsuited for exposure to acidified corroding media. This is a point of special importance for wire rope makers.[2]

The validity of the conclusions arrived at in the above research receives a measure of confirmation in the present research, as is evident from a consideration of the data in Table X., referring to commercially pure iron and the carbon steels. The wrought irons are not strictly comparable from this point of view, their increased solubility in acid being due to the galvanic activity of the

[1] Hadfield and Friend, *Journal of the Iron and Steel Institute*, 1916, No. I. p. 48.

[2] See Stead, *ibid.*, p. 72.

various non-homogeneous layers, as is evidenced by the deep etchings induced in acid solution shown in Fig. 3 (Plate I.). The effect of manganese in masking the increased corrodibility caused by addition of carbon to steel has already been noted (Tables XI. and XII.).

INFLUENCE OF COPPER.

The problem as to whether or not the addition of copper to steel is advantageous from the point of view of corrosion is one that has, in recent years, exercised the minds not of metallurgists only, but of steel manufacturers in general. In this connection, therefore, the results obtained with the steel marked HCU, containing 0·15 per cent. of copper, are particularly interesting. For the sake of convenience the mean results for commercially pure iron, wrought iron, and the carbon steels, as abstracted from Table V., are given below.

TABLE XIV.—*Influence of Copper on Steel.*

The data refer to losses in weight, expressed in grammes, per 1000 square inches of surface.

Metal.	Continuous Tap-Water.	Alternate Wet and Dry.	Continuous Salt Water.	Dilute Acid, 0·5 per Cent. H_2SO_4.
Cupriferous steel . . .	565	212	420	73
Commercially pure iron .	569	...	336	76
Mean of twelve wrought irons	564	194	414	461
Mean of nine carbon steels .	580	203	468	231

The high resistance offered to acid attack by the cupriferous steel is noteworthy and quite in harmony with earlier results under like conditions, notably those of Breuil,[1] the copper content of whose steels ranged from nil to 4·0 per cent. At a time when acid tests were regarded as useful acceleration tests, results of this kind encouraged the belief that cupriferous steel would offer high resistance to corrosion under service conditions. Many tests have therefore been carried out with varying neutral corroding media, using steels containing up to 2 per cent. of copper, and

[1] Breuil, *Journal of the Iron and Steel Institute*, 1907, No. II. p. 1. Also Bell and Patrick (*Journal of the American Chemical Society*, 1921, vol. xliii. p. 452), who worked up to 5 per cent. copper; Stead, *Journal of the Iron and Steel Institute*, 1916, No. I. p. 72.

the results have proved astonishingly conflicting. In some cases the influence of the copper would appear to have been highly beneficial[1]; in other cases the results are uncertain,[2] whilst in yet others it is claimed[3] that the copper is deleterious—a sure sign that all the factors have not been thoroughly placed under control. The results of the present research clearly indicate that the addition of small quantities of copper to steel exerts a minor influence upon the corrodibility of the metal in neutral corroding media. In tap-water and in salt water there is nothing to choose between the cupriferous steel and the wrought irons, all of which possess a slight advantage over the steels; in the alternate wet and dry tests the non-cupriferous metals proved slightly superior. In all cases, however, the differences are relatively small, being but slightly greater than the usual eccentricities manifested between different specimens of apparently similar metals.

Influence of Nickel and Chromium.

The influence of nickel and chromium, both separately and together, upon the corrosion of iron has been studied by many metallurgists, both from a purely scientific and a commercial point of view. Berzelius was aware, at the beginning of last century, that nickel steels are more resistant to corrosion than ordinary carbon steels, and the fact that meteoric iron, which usually contains alloyed nickel, exhibits but little tendency to rust, has long been observed. The general conclusion arrived at from a study of a large number of nickel steels appears to be that the amount of alloyed nickel must not be less than 2 or 3 per cent. if its retarding influence upon corrosion is to be appreciable. There are mechanical difficulties in the treatment of such steels, however, quite apart from their cost, and even such high nickel alloys as invar, which contains some 36 per cent. of nickel, have been observed by the author to manifest troublesome pitting under certain conditions. Chromium tends to retard corrosion in neutral solution, and "stainless" metals, containing from 12 to 14 per cent. of chromium, are extraordinarily resistant to the action of fresh water and to alternate wet and dry. In sea-water they tend to be more severely attacked, but specimens HS, FS, FS2, S19 are seen (Table XV.) to have withstood the action of salt water remarkably well; organic acids exert but little influence, whilst dilute mineral acids attack them with ease. Nickel chromes are fairly resistant to neutral corrosion, and sometimes highly resistant to acid attack, but in commercial brands the percentages of nickel and chromium respectively are usually low.

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[1] See Williams, *Iron Age*, Nov. 29, 1900, from *Proceedings of the Engineers' Society, Western Pennsylvania*, 1900, vol. xvi. p. 231; Stead and Wigham, *Journal of the Iron and Steel Institute*, 1901, No. II. p. 122; Walker, *ibid.*, 1911, No. II. p. 649; Buch, *Stahl und Eisen*, 1913, vol. xxxiii. p. 1244; Müller and Wedding, *ibid.*, 1906, vol. xxvi. p. 1444; Dillner, *ibid.*, 1906, vol. xxvi. p. 1493; Crowe, *Proceedings of the Cleveland Institution of Engineers*, 1909, p. 148.

[2] See Bauer, *Stahl und Eisen*, 1921, vol. xli. pp. 37, 76; Hadfield, *Minutes of Proceedings of the Institution of Civil Engineers*, 1921–22, vol. ccxiv. Part II.

[3] See Cushman, *Trans. American Electrochemical Society*, 1921, vol. 39, p. 99.

All of these points are borne out very clearly by the results in Tables III., IV., and V. The data, together with other earlier results, are expressed relatively to the corrosion suffered by mild steels under similar conditions in Table XV., which summarises existing quantitative knowledge on the subject.

The results are, of course, only approximately comparable, for the various carbon steels, used as standards, not being identical, could obviously not be expected to corrode at exactly the same rate. The error, however, will not be very great, inasmuch as good steels of average composition usually corrode at approximately the same rates, as has been shown by the extensive researches of Parker,[1] Rudeloff,[2] Howe and Stoughton,[3] and others.[4] In the last column of the table, results obtained with nitric acid are omitted, as they are not comparable with those obtained with hydrochloric and sulphuric acids, in consequence of the well-known but ill-understood passivifying action of the nitric acid, which produces disturbing effects. Further, several otherwise useful researches have had to be excluded from this list, owing to lack of sufficient published experimental details to render comparison possible.

The addition of 0·4 per cent. of tungsten (steel S12) appears to be without appreciable influence on the corrodibility of the nickel chromium steel (Table V.).

[1] Parker, *Journal of the Iron and Steel Institute*, 1881, No. I. p. 39.

[2] Rudeloff, *Mitteilungen aus der königlichen technischen Versuchsanstalt*, Berlin, 1902, Part XX. p. 83.

[3] Howe and Stoughton, *Proceedings of the American Society for Testing Materials*, 1908, No. 8, p. 247.

[4] The present research confirms this for modern steels.

TABLE XV.—*Influence of Nickel and Chromium on the Corrodibility of Iron.*

No.	Identification Mark.	Authority and Date.	Nickel per Cent.	Chromium per Cent.	Relative Corrosion.				
					Fresh Water.	Alternate Wet and Dry.	Salt Water.	Dilute Acid, 0·5 per Cent. H_2SO_4.	50 per Cent. H_2SO_4.
1		Crowe (1909)[1]	2·6–2·9	...	...	...	98	...	...
2		Howe (1900)[2]	3·03	...	80	67	83	...	...
3		Wiggin (1895)[3]	3·03	...	...	...	50	...	...
4		Friend, Bentley, and West (1913)[4]	3·72	...	109	61	84	55	...
5		Riley (1889)[5]	5·00	...	...	...	...	83[8]	...
6		Diegel (1903)[6]	6·14	...	...	...	65	...	...
7		Friend, &c. (1913)	6·14	...	107	44	85	63	...
8		Riley (1889)	25·00	...	...	...	...	1[8]	...
9		Howe (1900)	26·00	...	32	30	32	...	...
10		Friend, &c. (1913)	26·24	...	23	10	44	8	...
11		Diegel (1903)	29·7	...	...	...	26	...	...
12		Friend, &c. (1913)	...	1·12	73	109	80	223	...
13		Hadfield (1892)[7]	...	1·18	...	...	...	...	44
14		Friend, &c. (1913)	...	3·58	61	25	40	61	...
15		Hadfield (1892)	...	5·19	...	...	...	...	64
16		Friend, &c. (1913)	...	5·30	59	19	30	78	...
17		Hadfield (1892)	...	9·18	...	...	...	...	75
18	FS	Friend (1923)	...	11·73	5	...	5	...	...
19	FS2	"	...	11·73	8	...	6	...	...
20	HS	"	...	13·40	8	...	5	80	...
21	S19	"	0·54	12·75	3	12	21	117	...
22	S16	"	1·89	0·84	88	78	100	116	...
23	S10	"	2·88	0·10	95	100	93	73	...
24		Friend, &c. (1913)	3·4	1·00	101	60	107	132	...
25		"	3·5	1·12	108	68	108	413	...
26	S8	Friend (1923)	3·52	0·05	86	83	82	30	...
27	S2	"	3·53	0·67	84	70	85	38	...
28	K1	"	3·66	1·05	84	78	97	55	...
29	S17	"	5·80	0·14	77	77	81	18	...

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[1] Crowe, *Proceedings of the Cleveland Institution of Engineers*, 1909, p. 148.

[2] Howe, J., *Journal of the Iron and Steel Institute*, 1900, No. II. p. 567. Wrought iron taken as standard.

[3] Wiggin, *ibid.*, 1895, No. II. p. 164. The open-hearth steel used by Wiggin is taken as the standard in preference to the Bessemer steel also used by him, since the carbon and phosphorus content of the open-hearth steel more closely approximates to that of the nickel steel used. Corroding medium-hot 10 per cent. NaCl solution.

[4] Friend, Bentley, and West, *ibid.*, 1913, No. I. p. 388. The results for the six-month exposures only are given.

[5] Riley, *ibid.*, 1889, No. I. p. 45. The data given by Riley are very sparse, and greatly reduce the value of the work.

[6] Diegel, *Verhandlungen des Vereins zur Beförderung des Gewerbfleisses*, 1903, vol. v. p. 157.

[7] Hadfield, R. A., *Journal of the Iron and Steel Institute*, 1892, No. II. p. 92.

[8] Hydrochloric acid.

It will be observed that, whilst in neutral solution the chromium steels are less rapidly attacked than ordinary carbon steels, their behaviour towards acid is very eccentric. The 1·12 chromium steel, No. 12, was very severely attacked by the 0·5 per cent. sulphuric acid, and unless this is attributable to segregation in the particular disc employed, it would appear that a little chromium favours the solution of steel in acid. This would agree with the observations of Stodart and Faraday [1] and Gruner,[2] and it is also interesting, in connection with the observation of Monnartz,[3] that the presence of alloyed chromium increases the solubility of iron in nitric acid, the maximum solubility being observed with 4 per cent. chromium. Above this percentage the solubility falls off, until with 20 per cent. of chromium the alloy is practically insoluble in nitric acid. Although Hadfield's experiments were carried out with much stronger sulphuric acid than those of the author, the agreement of steels Nos. 14 to 17 is very remarkable, apparently indicating the existence of an optimum chromium content which yields the maximum resistance to acid attack, and that if this amount be either not reached, or else exceeded, a more corrodible alloy is the result.[4] From the above it is evident that the results obtained in acid corroding media give relatively no clue to the corrodibility of the metal under ordinary conditions of exposure. This again emphasises the fact that acceleration tests as usually carried out with acids yield very misleading results—an observation to which the present author has repeatedly called attention.

The nickel chromes usually resist dilute acid exceedingly well, although steels Nos. 24 and 25 are badly attacked.

In conclusion the author desires to express his appreciation of the grant awarded to him by the Carnegie Scholarship Committee which is enabling this work to be carried out.

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[1] Faraday, *Annales de Chimie*, 1822, vol. xxi. p. 73.

[2] Gruner, *Annales des Mines*, 1881, vol. xx.

[3] Monnartz, *Metallurgie*, 1911, vol. viii. pp. 161, 193.

[4] Compare Jüptner, *Stahl und Eisen*, 1899, vol. xix. p. 242, who points out that the composition of the alloy of chromium in steel depends upon the percentage of chromium. Hence its resistance towards corrosion may be expected to vary likewise.

Carnegie Scholarship Memoirs, 1923.]

Iron and Steel Institute.

DETERMINATION OF THE CORRECTIONS TO OPTICAL PYROMETER READINGS TAKEN DURING STEEL MAKING AND CASTING.

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Summary of the Report.

1. The difficulties met with during temperature observations in the furnace and in the open are discussed (p. 32). It is pointed out that, owing to the reflecting power of slags, light is reflected from hotter flames, or absorbed from cooler objects when there is no flame. Feeding, apart from the local drop in temperature, may cause low results if the materials charged give off fumes. Such materials are fluorspar, mill-scale, and manganese alloys. During teeming different results are obtained by sighting on the stream and on a plane surface such as that in the mould or in a trough. The presence of chromium in the steel increases this difference.

2. Evidence was obtained that the optical pyrometer in use was giving low results. A black body furnace was constructed and a calibration of the pyrometer was carried out (p. 38).

3. The optical conditions in the open-hearth being complicated by flames hotter (apparently) than the bath, and by loss of radiation through the open door, it was first necessary to determine the extent of departure from black body conditions under different circumstances. It has been found that there is an average difference of approximately 40° C. between the apparent temperatures of flame and slag surface, and also there is an apparent fall of 30° C. when flames clear from the hearth during a reversal. From the average of a large number of readings it can be stated that if 32° C. is deducted from the temperature taken with gas on, the result will be the same in 88 per cent. of the cases as if luminous flames had been absent—the accuracy being ± 10° C. (p. 42). This correction has been found to hold for acid and basic charges and at all stages of working from level melted to tapping.

In order to decide whether the temperatures obtained in absence of flame were true temperatures, series of readings were taken during tapping. It was assumed that the last metal and first slag which come together had been contiguous layers in the furnace, and therefore at the same temperature. The true metal temperature was obtained by correcting the observed temperatures for low emissivity. From the true and apparent slag temperatures the emissivity of the latter was obtained, and then the last slag temperature (assumed to be the upper layer in the furnace) was corrected by this value. This correct slag temperature was then compared with the last temperature taken in the furnace, and it was found (p. 46) that the latter was about 35° C. lower than the former. This correction is approximately balanced by that due to reflection from flames. *Hence to a close approximation it can be taken that, under the conditions described in the report, the temperatures taken in the furnace with the gas on are the true temperatures.*

The average apparent emissivity of acid and basic slags as determined by the above method is 0·56 and the average equivalent emissivity of the furnace is 0·80, the limits found being 0·65 to 0·95. A standard peep-hole would give a much more uniform value, and this would tend towards greater reliability.

4. The question as to whether temperatures obtained on small streams are low or not due to curvature of the surface, chilling, &c., was decided by sighting consecutively on the ladle stream and on metal in troughs, and again on the trough stream. By series of readings taken and extrapolated backwards it was found that after five minutes in the ladle, the steel temperature had fallen 30° C. (ladle stream) and 7° C. (trough surface). By calculation it can be shown that after five minutes the steel should have fallen approximately 30° C. Hence it appears that temperatures taken on the ladle stream and corrected for an emissivity of 0·40 are correct.

The loss in temperature in passing through the trough is about 5° C.

The results of previously published work are considered in connection with those here given.

The report concludes with a short account of the application of the results to the steel-making process.

INTRODUCTION.

Whilst much work has been done on the theoretical principles of optical pyrometry, the technical applications of the results have not progressed to the same extent, probably owing to the complicated nature of the optical laws involved, and, what amounts to the same thing, a lack of trained assistants who can interpret the results obtained. Consequently the now largely used optical pyrometer is generally employed as an instrument giving comparative readings under similar conditions, and not for determining true temperatures. On the general steel plant, which has to cope with material requiring not only wide ranges of composition but also variations in the method of teeming, distribution of pipe or blowholes (and in certain cases, of nonmetallic matter), some more scientific method of control becomes yearly of more vital importance. It is hoped, therefore, in this Memoir to examine the optical conditions at the steel-making furnace in such a manner as to make it possible for even untrained assistants to record true temperatures, both during the process and in the equally important casting operation.

The chief objection to the use of a pyrometer is that the results in themselves are of little value, the temperature being only one of many factors, all more or less vaguely understood, which determine the " condition " of the bath. The present methods of ascertaining the " heat "—namely, the bar test and the spoon sample fracture test—give an idea at once of the " condition," that is, of all the factors, and so are more readily interpreted.

It is now well known that temperature plays a most important part in defining the macrostructure of steel ingots, and the relationship between the latter and the tendency of ingots to crack, clink, or burst in forging is fairly well established. Also in certain cases it is useful to have a record of the temperature of the furnace structure during charging and melting.

It seems, therefore, of first importance that the temperature of the charge should be known during the working as well as during the tapping, particularly in those cases where the quality of the steel calls for the careful regulation of the casting temperature. For example, in group casting uphill, the natural gradient in the bath (coolest metal on the bottom) is relied upon to give a similar gradient in the ladle, and the " head " of temperature then tends to even up the heat losses during teeming. If, on the other hand, this gradient be reversed, as when the metal has been working hot, and heat has been slackened off towards the end, the metal first out will be hottest with a consequent maximum tendency to cracking in the earlier groups.

A further use for true temperature determinations lies in the estimation of the total heat capacity of the furnace for the purpose of determining the efficiency of the unit.

Reference will be made later to the work of the Bureau of Standards, and to the data collected in two symposia on pyrometry held by the Faraday Society and by the American Institute of Mining and Metallurgical Engineers respectively. A perusal of these data shows that there is still a considerable amount of technical work necessary, both on the purely pyrometrical side and on its application in metallurgy.

Scheme of Present Investigation.

The aim throughout the present Memoir has been to make the data generally applicable as far as possible, and not such as could only be obtained under special research conditions. Most of the technical observations have been taken by two observers who knew nothing of the theory of optical pyrometry, and whose readings are therefore unbiased. In all some 700 charges were followed through, from melting to teeming. They covered a period of seven or eight months, and the observations refer to both acid and basic charges. The steels made varied from dead-soft to 1·50 per cent. carbon, and included special steels. Generally some particular data were being aimed for, and in such cases observations were taken over two or three months, so as to get them under as varied conditions as possible.

1. *Measurements in the Furnaces.*—These were taken at all stages of working, under the following conditions :

(*a*) Apparent temperature of the slag surface with flames in the furnace.

(*b*) Apparent temperature of the actual flames.

(*c*) Temperature of the slag surface when there were no flames in the furnace.

From these data it is hoped to obtain a correction for light reflected from the flames.

2. *Tapping Temperatures.*—Series of readings were taken during tapping of both metal and slag. By applying corrections for emissivity of the metal, its true temperature can be obtained, and by working backwards from this the true temperature of the slag can be found. The difference between the latter and the last temperature taken under (1*c*) gives data for obtaining the departure from black body in the furnace. (This involves the assumption that there is no loss of heat in the launder.)

3. *Teeming Temperatures.*—Quite apart from the emissivity correction, there are several possibilities of low readings being obtained on the small ladle stream. In order to arrive at the magnitude of the necessary corrections, readings have been taken during trough teeming:

(*a*) On the ladle stream as usual.
(*b*) On the level surface of the molten steel in the trough.
(*c*) On the stream from the trough nozzle.

The reading taken in the centre of the trough surface, where there is constantly fresh metal being exposed, should be correct, so any departure from this serves as a basis for correcting the other two.

4. *Emissivity Determinations.*—As a check on the values obtained under (2), calculations of the emissivity of slags have been made from the data obtained at the furnaces. The work of the Bureau of Standards has shown that the emissivity of steel does not vary appreciably over wide ranges of composition.

As mentioned previously, one of the chief obstacles in the way of a more general adoption of the pyrometer as a means of control is the difficulty of applying the results. It has been considered, therefore, to be within the scope of this Memoir to set out the difficulties of obtaining true temperatures, and also to give examples of the methods of applying the observations to advantage.

Difficulties met with in obtaining True Temperatures.

These difficulties fall definitely into two classes, according as they refer to measurements inside or outside the furnace. As the two sets of conditions are different they will be considered separately.

(*a*) *Furnace Temperatures.*—During melting down, owing to the large volume of flame, it is necessary to wait for a reversal, and to take the temperature of the already molten charge. Generally speaking, the variations in the solid charge will be very great. Once the bath is level continuous readings can be commenced.

The first difficulty met with is that due to luminous flames in the furnace. The emissivity of the slags and brickwork is about 0·65, which means that they reflect some of the light received in excess of that which they are themselves emitting. If the flames are apparently hotter than the slag surface, they are emitting more intense light than the latter. Owing to the reflecting power of the slag, &c., the intensity of the light received in the pyrometer from the slag surface is greater than it would be if there were no flame—that is, a high value is obtained for the temperature. It should be noted that if non-luminous gas (as, for instance, by-product recovery gas) is used for heating, this factor does not arise.

Unless special provision has been made, temperatures must be taken through the open door. By waiting for a reversal readings can be taken when there is no flame in the furnace, but the conditions are not now similar to those under which the pyrometer was calibrated, falling between perfect black body and free radiation conditions. The extent of this departure from a black body will vary, and it cannot be predicted, but its effect is to give a low value for the temperature. If a standard position be chosen, a reasonably constant correction can, however, be made. By always using the middle door, it will be found that there is generally sufficient gas pressure to keep out cold air which would tend to chill the slag surface.

When the charge comes to the boil, the temperature of the surface is very erratic. The bubbles of gas are generated in lower and, therefore, cooler layers, and the slag thus brought to the surface appears darker than the surrounding liquid. This condition soon rights itself, owing to the violent agitation evening up the temperature of the bath.

Feeding, especially with limestone, causes a considerable local drop in temperature, which may persist for ten minutes. It is thus necessary for the observer to keep in constant touch with the working of the charge in order to avoid or note such times. Serious difficulty does arise, however, in the case of (*a*) heavy lime feeds in basic charges, and (*b*) fluorspar feeds. Lime floats on the surface for a long time before being absorbed, and if lumps accumulate it is difficult to adjust the intensity of the general field in the pyrometer, owing to these darker objects. Fluorspar contains as impurities lead, zinc, and strontium. The two former are evolved as dense white clouds, whilst the latter, even in small quantities, imparts its characteristic red colour to the hot gases in the vicinity. These fumes and coloured gases absorb some of the light coming from the portion of the bath, the temperature of which is being measured, and so a low result is obtained.

Whilst the temperature of the slag is of importance, that of the metal is more so. Silicates in general are bad conductors of heat, but the violent reactions during the boil bring metal and slag into intimate contact, and so aid the heat transfer. With thin slag blankets, such as are common with acid charges, the difference in temperature between slag and metal is probably negligible. In basic charges, however, where eight to ten inches of slag is common, conditions do arise when the temperature gradient through the bath must be appreciable ; for instance, when a tapping heat is rushed on near the end of the boil when the bath is becoming quiet.

From this summary of the furnace conditions, it will be seen that most of the difficulties can be avoided once they are recognised. The two serious ones are (*a*) the questionable extent of the departure from black body conditions, both with flame present and absent, and (*b*) the relationship between slag temperature and that of the metal.

(*b*) *Tapping and Teeming Temperatures.*—Practically the only difficulty in the way of taking temperatures during tapping arises from fumes and flames (in the case of basic charges carburised in the ladle). These have been dealt with in previous papers, and generally they can be overcome by selecting a suitable position. There is another phenomenon which can only be overcome by constant practice, namely, the peculiar iridescent sheen which appears on the surface of liquid steel in motion. This is probably an interference effect in a thin oxide film, for the intensity of the light received varies with the viewing angle. Consequently the ripples cause light and dark shades, ever changing, in the photometric field, and this has to be matched against the even field of the standard lamp.

With the teeming operation, a number of possibilities arise which lead one to think that the temperatures obtained are too low. The narrow stream forms only a thin band of light across the field (the Cambridge pyrometer is referred to throughout), filling only about one-tenth of the diameter in many cases. To this visual difficulty is added the one previously mentioned (surface sheen).

Theoretically, the pyrometer should be sighted normally on to the surface, the temperature of which is to be measured, but since the stream is more or less cylindrical and the Cambridge pyrometer uses the whole of this surface, only a small proportion of the light used is emitted approximately normal to the surface. If the light is polarised at the surface of liquid steel this curvature must affect the reading. This correction becomes negligible in the case of tapping temperatures, for the stream is then broad enough to admit of comparing the centre of the stream with the standard field.

TABLE I.

Quality.	Temperatures.		
	Stream.	Plane Surface.	Difference.
0·35 per cent. carbon, NiCr .	1570	1600	30
0·35 ,, ,, .	1430	1495	65
0·35 per cent. carbon, NiCrMo	1460	1500	40
0·35 per cent. carbon, NiCr .	1460	1470	10
0·35 ,, ,, .	1460	1480	20
0·35 ,, ,, .	1440	1480	40
0·35 ,, ,, .	1460	1490	30
0·35 ,, ,, .	1440	1470	30

Since the stream of metal from the ladle is in contact with the atmosphere, it might be imagined that the surface layer might be slightly chilled—that is, that a steep temperature gradient might exist. From experience, however, it is found that the total correction for this error and the previous one is not greater than 20 ° C. in normal practice, so that, separately, neither can be very serious. However, under certain conditions, these corrections may amount to 40° C., as shown by Table I. (p. 34).

These data were obtained by sighting on the stream and comparing the last temperature so obtained with the temperature when sighting on the metal surface in the mould as it was being churned up by the stream of metal. In this manner fresh metal was continually exposed and surface cooling thus reduced to a minimum. All these casts contained chromium (about 0·5 per cent. to 1·5 per cent.), along with other special elements, and it is quite possible that oxidation of the chromium in such steels might give a surface film of oxide having different properties from the metal itself. These readings serve to illustrate the fact that considerable caution is necessary in accepting optical pyrometer readings, and to show that it is necessary to take local conditions into account. The chief and most constant correction to apply to the optical readings on molten steel in the open is that due to low emissivity. Owing to the nature of the surface, the intensity of the light emitted by molten steel and slag is respectively only 40 per cent. and 65 per cent. of that of a perfect radiator at the same temperature. Consequently, since the pyrometer (as mentioned previously) is calibrated against a perfect radiator or " black " body, the apparent temperatures of steel and slag are considerably low—approximately 130° for the former and 80° for the latter in the neighbourhood of 1600° C.

It will be recognised that the difficulties met with in taking temperatures in the open are as serious, and call for the same discretion on the part of the observer, as in the case of temperatures in the furnace.

Calibration of the Pyrometer.

Although the instrument used was new, and was accompanied by a National Physical Laboratory certificate, it was evident from time to time that the readings obtained were too low. The evidence from which this became established was derived from several sources.

(*a*) A number of cases occurred in which casts of steel containing only 0·10 to 0·15 per cent. carbon were cooler than usual, and according to the pyrometer the temperature at which the steel finished teeming was below the freezing point. From the latest determinations of the melting point of iron (1530), it would appear that dead soft steel would begin to freeze between 1510° C. and 1520° C., and in order to run through a 1½-inch nozzle at least 50° C. of superheat would be necessary. In the following table data are given relating to a few casts which were noticeably cooler than usual :

TABLE II.—*Temperatures on Cool Dead Soft Steel Casts.*

Composition.		Pyrometer Reading.	Corrected for Emissivity 0·40.	
Carbon.	Manganese.		Original Calibration.	New Calibration.
0·13	0·44	1352	1470	1540
0·11	0·41	1354	1472	1542
0·12	0·40	1348	1466	1535
0·16	0·49	1348	1466	1535
0·11	0·45	1350	1468	1538

Each of these casts ran without leaving a skull, so it is clear that even allowing 20° to 30° C. for polarisation and chilling effects (see section dealing with this correction), the temperature as obtained from the original calibration, assuming only the figure 0·40 as the emissivity of liquid steel, is too low. Since a variation of 0·05 in the emissivity value only makes a difference of 20° C. between 1300° and 1400° (apparent), it will be seen that using the figure of 0·37 as obtained experimentally (Burgess and Foote) would only increase the readings by 15° C.

(*b*) The two scales of the Cambridge pyrometer overlap in the range 1200° to 1400° C., and readings taken in this region, sighting on the same hot body, should agree. A series of tests, made under conditions described below, gave the results shown in Table III.

TABLE III.—*Comparison of the Two Scales of the Optical Pyrometer.*

Original Calibration.			New Calibration.		
Low Scale.	High Scale.	Difference.	Low Scale.	High Scale.	Difference.
1380	1340	40	1425	1402	23
1370	1335	35	1415	1395	20
1360	1320	40	1403	1380	23
1348	1305	43	1392	1373	19

These observations were confirmed by the author and the two assistants who obtained the technical data. It will be seen that there is a comparatively large difference between the two sets of readings on the original calibration; and owing to the greater ease of experiment at lower temperatures, as well as the fact that the temperature scale is better known below 1300° C., the lower scale is more likely to be correct. On the new calibration, whilst the discrepancy is not entirely removed, there is considerable improvement.

At the completion of the technical observations it was decided to attempt the calibration of the optical pyrometer against a thermocouple. The difficulties of doing this satisfactorily in an ordinarily equipped laboratory were recognised from the beginning, but it was thought worth while to make the attempt.

A Paul-rhodio couple, and indicator graduated up to 1600° C., was first subjected to a preliminary calibration at standard temperatures. The following is a list of the points used, together with the method in each case :

TABLE IV.—*Calibration Points for Paul-rhodio Couple.*

Substance.	Melting Point. Degrees C.	Method.
Aluminium	657	Crucible. Cooling.
Sodium chloride . . .	801	,, ,,
Silver	955	Wire in air.
Gold	1063	,, ,,
Copper	1083	Crucible. Cooling.
Nickel	1452	Wire in air.

The black body was constructed inside a Brayshaw gas-fired brick-testing furnace. The arrangement is shown diagrammatically in Figs. 1–2. It consists essentially of an enclosure approximately 30 cm. cube, heated by two air-gas burners placed diagonally, one at the front and the other at the back. The gas feed pipe is sufficiently large to fill the whole enclosure with flame, and with careful working local heating can be avoided. The brickwork surrounding the enclosure is about six inches thick, so that when once soaked the temperature can be kept very uniform. Inside this, the black body proper was supported on carborundum blocks, in such a manner that the flames could sweep all round it, and leave the enclosure by two ports near the bottom. The construction of the black body is shown in greater detail in Fig. 3. It consists of an outer alundum tube 2 inches internal diameter and 12 inches long, closed at one end by a refractory disc. A tightly fitting silica tube was placed inside this, and the disc to be sighted on was fixed as shown. The whole of this system was in the heated enclosure, but a second alundum tube,

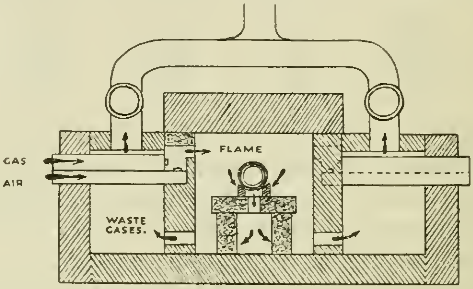

Fig. 1.

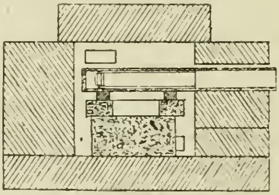

Fig. 2.

of the same dimensions as the first, was placed to continue to the exterior of the furnace. In view of the deleterious effect of silica on platinum at high temperatures, the couple was only inserted a short time before readings were to be taken with the optical pyrometer. When the furnace had soaked for several hours, the procedure was as follows. The uniformity of temperature within the enclosure was measured by drawing the thermocouple along from the disc, and taking readings. The following table indicates the degree of uniformity attained at different temperatures.

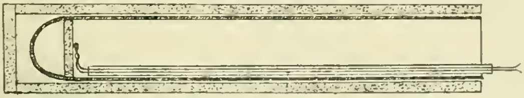

FIG. 3.

TABLE V.—*Temperature Uniformity in Black Body during Calibration.*

Temperatures taken with Thermocouple.

Disc.	Centimetres from Disc.										
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
844	844	...	846	...	842	832	...	825	...	...	...
905	907	...	904	905	905	...	908	...	...	...	905
990	...	995	...	...	...	...	...	995	...	...	...
1120	1118	...	...	...	1120	...	...	...	...	...	...
1191	...	1189	...	...	...	1195	...	...	...	1198	...
1380	...	...	1385	...	...	...	...	1392	...	...	...
1400	...	...	...	...	...	1407	...	1405	...	...	...
1510	...	...	...	...	...	...	...	...	...	1500	...

When the uniformity was satisfactory, the couple was returned to the face of the disc, and readings were taken with the optical pyrometer by three independent observers.

The calibration curve was constructed from these observations by plotting the reciprocal of the true absolute temperatures (thermocouple readings, + 273) against the values of log. tan ϕ (where ϕ is the angle of rotation of the analyser corresponding to the observed temperature). The relationship between these co-ordinates is a linear one, so the best straight line is drawn between the observed points. This is shown in Fig. 4. Then, by taking a number of points from this graph, and converting back to temperatures, the best calibration curve for the observations is obtained. This final curve is shown in Fig. 5, where crosses denote points from Fig. 4, and the dots represent the original observations.

Determination of the Departure from Perfect Radiator Conditions in the Open-Hearth Furnace.

Since the furnace is more or less completely closed, one might expect that for visible radiations it would be sufficiently near to a perfect radiator for corrections to be negligible. When the door is up, it is quite possible that excess radiation from some hotter part of the brickwork is reflected from the slag surface, and so tends to balance the loss of radiation through the open door.

It is, however, necessary to determine the effect of flames in the furnace, for these are always hotter, and in the case of ordinary producer-gas they are always luminous. The temperature obtained when the gas is off is a much more reliable guide, and so an attempt has been made to interpret the results obtained with the " gas on," in terms of " gas off " temperatures. This is one problem. Another is to determine whether the latter approach at all closely to true temperatures.

1. *The Difference between " Gas On " and " Gas Off " Temperatures.*—The visible radiation used by the optical pyrometer when sighting on the slag surface during the working of the charge is made up as follows :

(*a*) Radiation actually emitted by the slag surface.
(*b*) A certain amount reflected from flames.
(*c*) Radiation from various parts of the internal brickwork, which may be hotter or cooler than the slag surface.

When the gas is on, (*a*) and (*b*) are the important factors, for radiation from the brickwork, whether hotter or colder, is absorbed by the flames. When the gas is off, only factors (*a*) and (*c*) operate.

There is no ground for assuming that these three factors maintain the same relationship to one another under varying

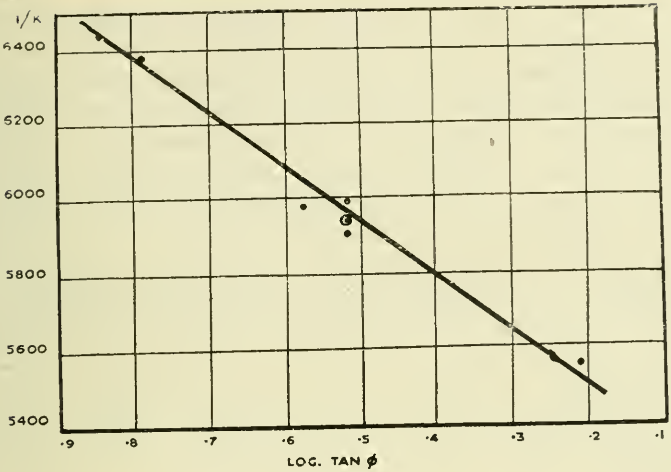

FIG. 4.

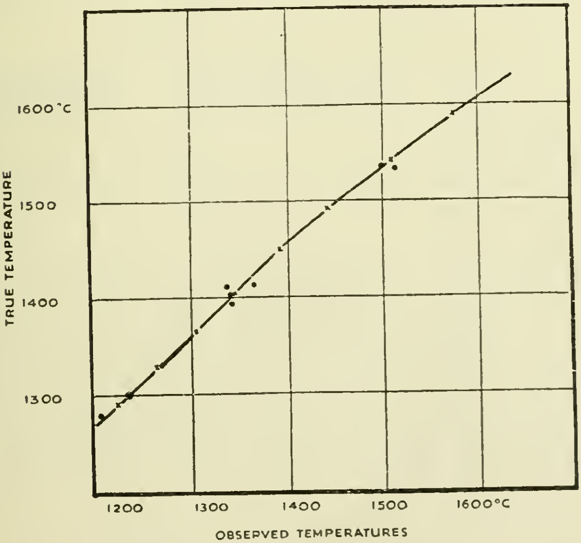

FIG. 5.

conditions, so that observations have been taken in as general a manner as possible.

The order in which the three readings are taken would at first thought appear to be of importance, but actually no consistent difference has been found, whether the flame temperature was taken first or last. In the former case the order would be : (1) Apparent flame temperature ; (2) slag surface with flame on ; (3) slag surface with furnace free from flame, taken during a reversal. In this case the regenerators are at their lowest temperature when the flame temperature is taken. In the second case, when the flame temperature is taken last, the regenerators are hottest. As mentioned above, no appreciable difference was found between the two methods, and so the results have been tabulated indiscriminately. In the cases recorded in the tables of Appendix I. the maximum time elapsing between the first and third reading by either method was three minutes. These observations may be taken as representative of the respective furnaces.

TABLE VI.—*Effect of Flames on Temperatures in Furnace.*

(Summary of Tables in Appendix I.)

Furnace.	Observer.[1]	No. of Observations.	Apparent Difference between Gas Temperature and Slag Temperature with Gas on, D_1.					Apparent Difference between Slag Temperature with Gas on and Gas off, D_2.				
			Avg.	Min.	Max.	Per Cent. within		Avg.	Min.	Max.	Per Cent. within	
						± 5°.	±10°.				± 5°.	±10°.
V Acid	B	46	41	30	52	78	96	36	12	50	65	85
W Acid	A	46	44	32	54	72	100	27	18	44	83	96
	B	46	42	20	60	57	85	34	17	51	54	85
U Acid	A	46	42	26	60	67	89	25	18	36	83	96
	B	46	44	27	61	70	89	34	25	51	72	93
X Basic	A	45	46	30	64	33	80	30	18	44	56	89
	B	43	42	31	66	74	93	33	10	46	63	86
Y Basic	A	46	43	28	58	65	85	29	17	46	63	85
	B	46	42	25	60	47	81	35	14	55	72	85
Z Basic	B	43	43	20	70	63	81	36	22	50	58	88

The results are summarised in Table VI., in which the difference D_1 is the apparent difference in temperature between the flame and the slag surface immediately beneath it, and D_2 is the apparent fall in temperature as the furnace clears of flame. These differences are a general average for each furnace under all conditions, at all stages from level melted to tapping, and for different qualities of steel. Since these results are only differences of temperatures, which in themselves are fairly near together, the actual figures given in Appendix I. have not been corrected to the new calibration.

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[1] The two technical observers have been designated "A" and "B."

Table VII.—*Total Average Results for the Effect of Flames.*

Type of Furnace.	Total No. of Observations.	D$_1$.			D$_2$.		
		Average.	Per Cent. within		Average.	Per Cent. within	
			± 5°.	± 10°.		± 5°.	± 10°.
Acid	230	43	70	90	31	53	88
Basic	223	43	57	83	32	53	88

From these results the following conclusions can be drawn :

(1) There appears to be no serviceable quantitative relationship between the difference of intensity of luminosity of slag and flame on the one hand, and the difference between slag luminosity with flame on and off respectively on the other hand. The average result, however, gives 43° C. as the former, and 32° C. as the latter. Hence, if a temperature observation is taken on the slag surface whilst the flame is on, and a deduction of 32° C. made, in 88 per cent. of the cases the result will be the same as would have been obtained with the gas off within 10° C. This is a very useful result, for in taking observations on a number of furnaces it is impossible always to be present at a reversal.

(2) This figure (32° C.) is equally applicable to basic and acid charges, provided that the precautions mentioned on pp. 32–34 are observed.

(3) The averages obtained from the results of the two observers are generally within 7° C.

(4) It was thought that a correction of this type would vary during the working of the charge, owing to differences in the amount of flame, and to variations in the relationship between

flame and slag temperature. That this is not so is shown by the following tables :

Table VIII.—*Showing the Constancy of the Difference in the Apparent Temperatures of the Slag Surface with Gas On and Gas Off.*

Temperatures with Gas On.	Average value of D_2.	Number of Observations.	Type of Furnace.
Up to 1520° . . .	29	54	Acid
1520° to 1560° . .	30	89	,,
1560° to 1600° . .	34	79	,,
Up to 1520° . . .	33	39	Basic
1520° to 1560° . .	30	94	,,
1560° to 1600° . .	34	83	,,

In this table the average values for the difference in apparent temperatures with gas on and gas off are shown in relationship to the actual temperatures. For this purpose the ranges (*a*) up to 1520°, (*b*) 1520° to 1560°, (*c*) 1560° to 1600°, have been taken as typical of the stages melting to boiling, boiling, and finishing respectively. There is no systematic variation.

2. *Do the "Gas Off" Temperatures approximate to True Temperatures?*—This is a more difficult matter to determine experimentally, but there are several lines of attack. It is necessary to obtain the true temperature of the bath in a manner which leaves as little doubt as possible that this has been attained. The author previously suggested [1] as a means of obtaining the true temperature, the insertion of a refractory tube into the molten slag, and sighting into this with the optical pyrometer as soon as it had taken up the temperature of the bath. The conditions would then be ideal. The method was tried by the Pyrometer Committee of the National Research Council (U.S.A.), who used an Acheson graphite tube temporarily immersed in the bath. From the accounts given in the report, this method does not appear to be at all practicable.

A much more easily applied method, though one which is not likely to give as accurate results as the former, is based on the optical properties of metal and slag. It seems to be a reasonable assumption that in the quiet bath, just before tapping, the contiguous surfaces of slag and metal are at the same temperature. In the furnace, however, only the upper surface of the slag can be sighted on, and this may be considerably different from the lower surface. If, now, during tapping, a series of observations is made at frequent intervals, the apparent temperatures of the previously adjacent surfaces will be obtained under freely radiating conditions. The assumption is made that the last metal out and the first slag out are the same portions of the bath as were in contact before tapping. Similarly, the last slag[1] out will be the same as was sighted on in the furnace. We thus get the following :

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[1] *Transactions of the Faraday Society*, vol. xiii. p. 301.

Free Radiation.	Emissivity.	True Temperature.
Apparent temperature of last metal using . .	0·40	gives . . *a*.
Apparent temperature of first slag gives . .	x	by using *a* in the formula below.
Apparent temperature of last slag using x as determined gives . .		a'.

The derived temperature a' should be the same as the last temperature taken on the slag surface in the furnace, if the conditions in the latter are equivalent to those of a perfect radiator.

Another method would be to assume the latter to hold, and to calculate the emissivity of the slag from the last temperature in the furnace and the last slag temperature out of the furnace. This value x' should be equal to x if the furnace temperature is a true one. The former alternative is the better from a practical standpoint, as any departure from perfect radiation conditions in the furnace is given immediately in terms of temperature.

The emissivity (x) of the slag is calculated from the following formula :[2]

$$\log_{\cdot 10} x = \frac{1}{\mathrm{T}} - \frac{1}{\mathrm{T}'} \cdot \frac{c \log . e}{\lambda}$$

where $\mathrm{T} = a + 273°$ absolute;
T' = apparent temperature of slag (C) in degrees absolute;
c = constant (14,500);
e = base of natural logs.;
λ = wave-length of light transmitted by eyepiece of pyrometer ($0 \cdot 65\mu$).

In arriving at the true temperature of the slag surface by this method, the only assumption is the value 0·40 for the emissivity of the clear metal surface. This is the value adopted by the Bureau of Standards as the best for technical practice.

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[1] Actually considerable chilling has generally occurred before the last slag appears, so that an earlier reading has to be used in practice.

[2] See Appendix II.

The observations on five furnaces are given in the tables of Appendix II., and are summarised in Table IX. From this table two facts stand out clearly :

(1) The average emissivity of the slags calculated from the technical observations is 0·56. The figure accepted by the Bureau of Standards is 0·65.

(2) The last reading in the furnace with door up and gas off is about 35° lower than that calculated from the slag tapping temperature.

TABLE IX.—*Departure of Furnace Conditions from Black Body.*

(Summary of Tables in Appendix II.)

Furnace Type.	No. of Casts.	Average Emissivity of Slag.					Correct Temp. Last Slag.	Last Temp. Furnace Gas Off.	Difference.	Equivalent Emissivity of Furnace.
		Quality of Steel.[1]								
		DS.	M.	H.	CrNi.	CrV.				
V Acid	32	...	0·54	0·54	0·52	0·55	1621	1584	37	0·79
W Acid	41	...	0·53	0·53	0·56	0·51	1611	1575	36	0·795
X Basic	42	0·55	0·56	0·56	...	...	1600	1569	33	0·81
Y Basic	35	0·57	0·56	0·59	...	...	1599	1568	31	0·82
Z Basic	36	0·55	...	0·56	...	...	1610	1574	36	0·795

[1] DS = Dead soft, 0·10 to 0·20 per cent. carbon. M = Medium, 0·20 to 0·60 per cent. carbon. H = Hard, 0·60 to 1·20 per cent. carbon.

This gives an equivalent emissivity of 0·80 for these furnace conditions.

The reason for the low slag emissivity might be as follows : Slag is a bad conductor of heat, and is in general a fairly viscous liquid. Air currents playing on the surface might, therefore, chill the exposed layer, even in the short time taken to flow down the launder. This would give a low apparent temperature, and so a low value for the emissivity. The difference in temperature represented by a change from 0·55 to 0·65 would be approximately 25°, and it is not difficult to imagine a chilling of the slag surface to this extent. Such a correction to the slag tapping temperature (if further experiments should establish it) would not affect the difference between the last slag temperature and the last taken in the furnace, for the former is referred back to the metal temperature as standard and the modified value for the emissivity automatically cancels any addition made for cooling effect.

Reference to the minimum and maximum differences ($a'-b$) in Appendix II. will show that the equivalent emissivity of the furnace (door open) varies between 0·95 and 0·65. One would expect this variation under the conditions, for it is generally necessary to sight on to the slag bath near the door.

The results obtained from this information can be summed up as follows :

(1) The average emissivity (apparent) of open-hearth slags is 0·56, as distinct from the accepted true emissivity of 0·65.

(2) The average equivalent emissivity of open-hearth furnaces, sighting on to the slag surface through an open door, and with flame absent, is 0·80, the limits actually found being 0·95 to 0·65, depending evidently on the extent of the door aperture and the exact position of the spot sighted.

(3) It follows from this that, on an average, the readings taken in open-hearth furnaces under the conditions cited are 35° low. It will be remembered that, as a result of the investigation on the effect of flames (p. 42), it was found that temperatures taken with the flame on were of the order of 32° high. It follows, therefore, that the effect of flames, in general, just balances the departure from black body conditions. Hence the temperatures taken with flame on are practically true temperatures.

(4) The corrections to furnace temperatures (with flame off) will be as follows for an emissivity of 0·80 :

Observed Temperatures.	Addition.
1350	27
1400	28
1450	30
1500	32
1550	34
1600	36

(5) It would obviously be a big advantage if a " peep-hole " could be made in the furnace side, so that observations could be taken on the slag during a reversal without opening the door. In this case the temperatures would probably be approximately true values.

Typical curves embodying the corrections so far considered are shown in Figs. 6 and 7. In Fig. 6 some of the observations were taken immediately after ore feeds, and these fall below the general curve. Two points are shown which were taken with

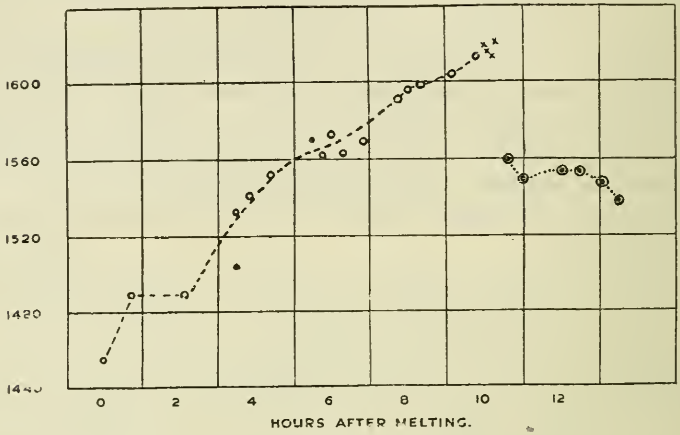

Fig. 6.—Heating Curves for Charges of Steel Finishing 0·50 per Cent. Carbon for uphill Run.

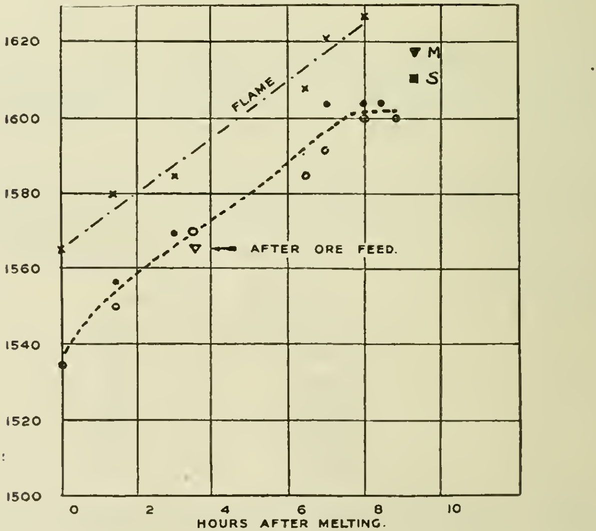

Fig. 7.

the bath free from flame, and these have been corrected for departure of the furnace from black body. The same remark applies to the "black" points in Fig. 7, and apparent flame temperatures are also given. The agreement here shown is quite general.

ARE THE TEMPERATURES OBTAINED ON SMALL-DIAMETER STREAMS LOW?

As mentioned previously (p. 34), one would expect that the temperatures obtained on ladle streams would be low, chiefly, it is thought, owing to polarisation effects at the curved surface.

Experiments have been made in the laboratory to decide whether there is any difference in reading due to the photometric field not being filled with light. An opening was made in the wall of a large uniformly heated enclosure, such that the field of the pyrometer was filled when at a distance of 3 feet. The opening was then cut down by covering it with metal plates in which slits of varying widths had been cut. In this manner a constant temperature can be observed with just the one variable. No difference in reading was obtained in cutting down to the ordinary size of image used when sighting on ladle streams. It is, of course, more difficult to match the intensity, but this does not introduce an error of definite sign.

Owing to the experimental difficulty of maintaining a small bath of steel at constant temperature in order to determine the effect of sighting angle, technical methods were again resorted to.

Advantage was taken of the method of teeming steel through troughs, to compare the apparent temperatures of metal issuing from the ladle (say $1\frac{1}{4}$-inch diameter stream), of the same steel in the trough where a clean surface is continually exposed sufficient to fill the photometric field, and of the small stream (about 1-inch diameter) issuing from the trough.

The results of observations on acid and basic steels are given in Table X. The angle of view of the trough surface would be approximately 45°, so that if there is any polarisation effect it will not be entirely eliminated even in this case. The average of fifty observations on twelve casts is that the apparent

TABLE X.—*Temperature Observations on Small Streams.*

X Furnace (Basic).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			Differences.	
		Ladle Stream. (1)	Trough Surface (2)	Trough Stream (3)	2 − 1	2 − 3
1266	1·33	1380	1422	...	42	...
		1370	1412	1362	42	50
		1365	1396	1358	31	38
		1354	1388	1352	33	36
1269	0·64	1395	1420	1345?	25	(75?)
		1380	1400	1370	20	30
		1363	1400	1375	27	25
1276	0·27	1436	1452	1434	16	28
		1434	1452	1432	18	20
		1424	1438	1422	14	16
		1418	1434	1416	16	18
1278	1·30	1418	1442	1420	24	22
		1418	1438	1414	20	24
		1406	1434	1404	28	30
		1390	1418	1388	28	30
1277	0·98	1425	1435	...	10	...
		1420	1440	1375	20	(65?)
		1390	1410	1375	20	35
		1395	1420	1395	25	25
1286	...	1414	1442	1414	28	28
		1410	1434	1400	24	34
		1390	1424	1388	34	36
		1386	1418	1382	32	26
		1378	1412	1374	35	38
Y Furnace (Basic).						
66	0·59	1398	1418	1396	20	22
		1396	1420	1394	24	26
		1392	1416	1388	24	28
		1392	1412	1384	20	28
67	0·57	1408	1420	1398	12	22
		1404	1426	1398	22	28
		1400	1418	1396	18	22
		1392	1418	1392	26	26
74	0·60	1390	1410	1375	20	35
		1365	1390	1360	25	20
75	0·50	1386	1410	1380	24	30
		1374	1400	1366	26	34
		1360	1388	1358	28	30
		1360	1384	1352	24	32
W Furnace (Acid).						
1058	0·59	1438	1458	1434	20	24
		1430	1448	1424	18	24
		1426	1440	1422	14	18
		1396	1428	1392	32	36
		1390	1418	1386	28	32
1060	0·32	1416	1441	1414	25	27
		1416	1434	1414	18	20
		1406	1424	1400	18	24
		1394	1424	1396	30	28
		1396	1418	1388	22	30
		1392	1402	1386	10	16
		1386	1400	1378	14	22

temperature of the trough surface is 24° higher than that of the ladle stream, and 28° higher than that of the trough stream. One would expect a small drop in temperature whilst passing through the trough, and this appears to be of the order of 5°.

Against the above view is that of Cosmo Johns, who considers that the difference in apparent temperatures of the ladle stream and trough surface is due entirely to the formation of an oxide film on the latter. Such a film would have a higher emissive power, and so a higher apparent temperature, than a clear steel surface. If this view be correct, it would be expected that the presence of a readily oxidisable element in the steel would accentuate such an effect. The observations in Table I. clearly indicate that this is so in the case of chromium.

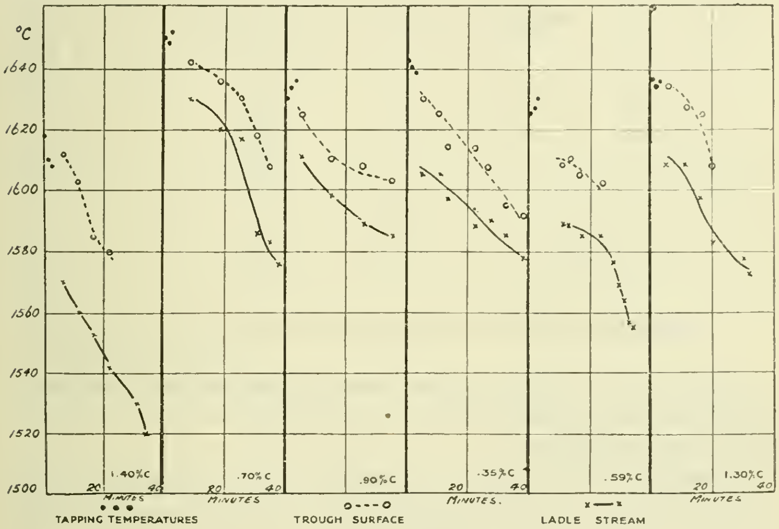

Fig. 8.

There is another method of deciding this point. Calculation leads one to expect that after the charge has been in the ladle for five minutes it will have given up heat to the ladle, which will have lowered its temperature by approximately 30°; this, of course, depending on the relative masses of ladle and charge, conductivity of the firebrick, &c.

In Fig. 8 the observations on six troughed casts have been plotted, and from Table XI. it will be seen that after five minutes the apparent loss of temperature as measured on the ladle stream and trough surface respectively is 30° and 7°.

It must therefore be concluded that the readings on the trough surface are high. Incidentally, this conclusion practically rules out the possibility of polarisation affecting the results to an appreciable extent.

TABLE XI.—*Apparent Fall in Temperature after Five Minutes in Ladle.*

Trough Surface.	Ladle Stream.
0	45
5	20
10	25
10	35
15	35
0	25
Average 7	31

CONSIDERATION OF PREVIOUSLY PUBLISHED RESULTS.

Before considering the application of the results obtained in the foregoing, it will be well to recall briefly the work and views of earlier investigators.

Taking first of all the Faraday Society Symposium on pyrometry, the paper of chief interest from the present author's point of view was that by Mr. Johns. His main conclusions are set out below :

(1) The average temperature of the bath surface is considered to be 1635° apparent—equal to 1766° C., assuming an emissivity of 0·50.

(2) The average temperature of the bath proper is 1470° apparent—equal to 1615° C.

(3) For a bath 16 inches deep, the total apparent rise in temperature is 15°, extending over a tapping time of five minutes. When the full slag stream appears there is a further apparent rise of 15° in two minutes, and the stream itself appears 15° hotter, due to difference between the emissivities of slag and metal respectively.

(4) The value of 0·65 for the emissivity of acid slags is considered to be much too high.

(5) The average loss of temperature between launder and commencing to teem is 30°.

(6) In trough teeming it is considered that there is a film of oxide on the surface of the metal in the trough away from the stream, and the higher emissive power of this causes a high reading to be obtained.

With regard to the actual results of observation mentioned in the first of these points, there is a variation of 50° from the average results set out in this Memoir (p. 51). In the author's opinion, however, the value of 0·50 for the equivalent emissivity of the furnace is far too low in general. If the value of 0·80 (as found in the present investigation to be the average of a large number of casts) be accepted, then the average temperature of the bath surface mentioned would be approximately 1670° C. instead of 1766° C. In view of the 50° difference between the average bath temperature (surface), it is remarkable that the values found for the actual bath in the two cases should be much nearer together, *e.g.*, 1615° (Johns) and 1603° (average of 180 casts by the author).

In the third point there is a serious difference of observation, for whereas a rise of only 15° was noted on the appearance of slag, in the present case a rise of 40° to 60° was generally noted. An apparent difference of 15° between contiguous layers of metal and slag would mean that the emissivity of the latter was very little higher than that of the former, say 0·44. As a result of a large number of observations, the author has come to the conclusion that the apparent emissivity is in general lower than the average value of 0·65 given by Burgess. This is accounted for by the chilling of the slag surface as soon as it leaves the furnace. On the other hand the value 0·44 certainly seems too low. The average observed value for many slags of varied composition is 0·56.

The fifth and sixth points raised have already been dealt with (p. 51), and the agreement is satisfactory.

Passing now to American publications, Burgess[1] gives some examples from American practice. It would appear that much steeper gradients obtain there, perhaps due to more rapid working; for instance he quotes two cases—heat 7–14 in which there was a fall of 80° in two minutes during tapping, and heat 12–36 in which a rise of 50° was noted. He gives as extreme cases tapping temperatures of 1710° to 1520°, and states that the temperatures of open-hearth baths are usually kept between 1600° to 1670°. The large temperature gradients mentioned are corroborated by Foote, Fairchild, and Harrison,[1] who say that the slag temperatures are as much as 150° C. higher than those of the metal during heating, but when the gas is shut off the slag cools rapidly, and may be 75° below that of the metal just before tapping. The author has not met with these extreme variations in English practice.

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[1] *Bureau of Standards Technological Paper* 91.

The more recent work done in America is recorded in the three reports of the Pyrometer Committee of the National Research Council.[2] These efforts were chiefly turned in the direction of obtaining more accurate data in the furnace by eliminating optical effects, *e.g.* by creating a black body in the bath. Trials were made in open-hearth furnaces using clay ends and graphite ends to built-up tubes. Both proved impracticable, the former cracking and the latter giving off smoke which obscured the end. Further experiments were made in electric furnaces, using Acheson graphite ends for the tubes and these were found to be quite satisfactory. Readings were obtained by sighting down the tube whilst immersed in the bath, and also by sighting on the end when it was raised above the slag surface, and as slag does not wet the surface of Acheson graphite, which has an emissivity 1, no correction for departure from blackness is necessary whether there is flame in the furnace or not.

From this it would appear that, although it is possible to create ideal optical conditions in the bath by means of a temporary black body, the difficulties and expense attending it make the method scarcely practicable for everyday control purposes, and hence the present attempt to analyse the results obtained under normal working conditions as found in technical practice, accepting those conditions as one finds them.

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[1] *Bureau of Standards Technological Paper* 170.

[2] *Pyrometry*. Published by the American Institute of Mining and Metallurgical Engineers, 1920.

APPLICATION OF THE RESULTS OBTAINED.

Whilst it was not a primary object of this report to set out the metallurgical rôle of temperature in steel making and casting, it would scarcely be complete without a brief reference to some of the possible applications of the results obtained.

Considering only the metallurgical aspect (*i.e.* ignoring any application to the furnace structure), two main problems present themselves :

(1) How does temperature affect the reactions taking place in the furnace ?

(2) What are the temperature considerations affecting the production of definite types of ingot ?

Taking these problems in this order, we can follow the reactions which occur from the charging of the cold metal. Oxidation of the iron and slag formation commence as soon as the charge begins to trickle down, and this is one of the most critical periods in the working of the charge. Naturally, the rate of melting and of oxidation depends to a large extent on the nature of the charge ; for whereas with small scrap offering large surface a rapid melting would occur, with a medium temperature, with heavier scrap a steadier melting with time to form a good slag would require a higher temperature. Steel making being a compromise from beginning to end, it is quite impossible to lay down any definite programme without consideration of the full details of the plant and materials available. Consequently it is impossible to say " Maintain a temperature of 1570° to 1600° C. during melting," or even such a vague statement as " Melt rapidly with high temperature," without taking into account the above details. With increasing knowledge of a particular plant, however, it should be possible ultimately to control the rate of melting pyrometrically, and so obtain the best condition of bath when level melted. In other words, a definite partition of certain common constituents of slag and metal could result from a controlled rate of melting. It is now recognised that the state of the bath when clear melted is one which is capable of exercising an influence on the whole process of steel making, and that under certain circumstances irreparable damage can occur during the melting operation. In this connection it is quite possible that the complete reactions are unknown. McCance[1] says, "Melt down rapidly and melt down at high temperature," but the charge can be melted too rapidly, especially in an electric furnace, causing a reaction which cannot afterwards be corrected by the use of deoxidisers, but which gives rise to blown ingots.

For a high quality of steel which must be as free as possible from dissolved oxide or nitrogen, and using medium scrap and pig for the charge, the author would suggest that the temperature of the bath when level melted should be 1540° to 1580° C. Feeding with ore, &c., will reduce the temperature 20° to 30° for a short time, and after this should follow a rapid increase to the maximum which should then be maintained during the working.

Figs. 9 to 11 show typical heating curves for such a class of steel of finished carbon content 0·50° to 0·60°.

In the case of basic charges, additions of limestone cause considerable fall in temperature due to the heat required to decompose the carbonate, and this heat loss should be taken into account. Appreciable local falls in temperature due to additions are shown in Fig. 13, in which the broken line shows the true course of the temperature and the full line the normal general course.

According to McCance,[2] the higher the temperature is during melting the lower is the rate of oxidation, and on this assumption he rules out direct oxidation by oxygen and carbon dioxide. He does not appear to take into account, however, the fact that higher temperature means quicker melting and therefore less time available for oxidation of the iron. Presumably also less slag would form, so that these two factors must be taken into account when considering the analysis of the melting slag.

When once melted, and all metal under a slag covering, there seems to be general agreement that the temperature should be as high as possible. The main reactions taking place in order are:

$$Si + 2FeO \rightleftharpoons SiO_2 + 2Fe \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$Mn + FeO \rightleftharpoons MnO + Fe \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$C + FeO \rightleftharpoons CO + Fe \quad . \quad . \quad . \quad . \quad . \quad (3)$$

These are all balanced reactions, and as such the equilibrium condition attained depends on the temperature as also on the relative concentrations of the reactants in slag and metal, tending towards (though in practice never attaining) a definite partition at a particular temperature.

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[1] *Transactions of the Faraday Society*, 1919, p. 214.

[2] *Loc. cit.*, p. 213.

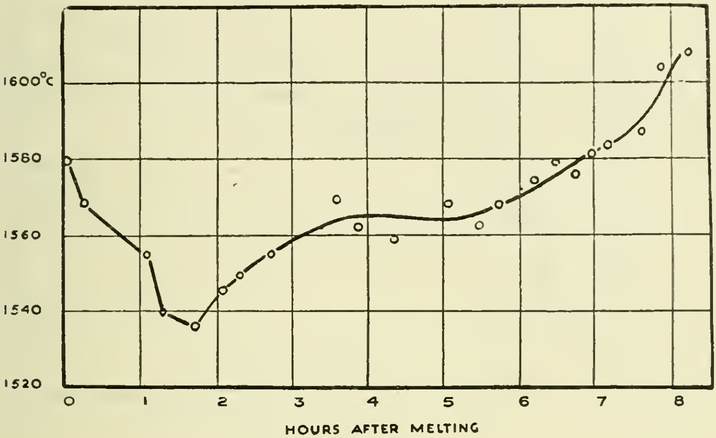

Fig. 9.

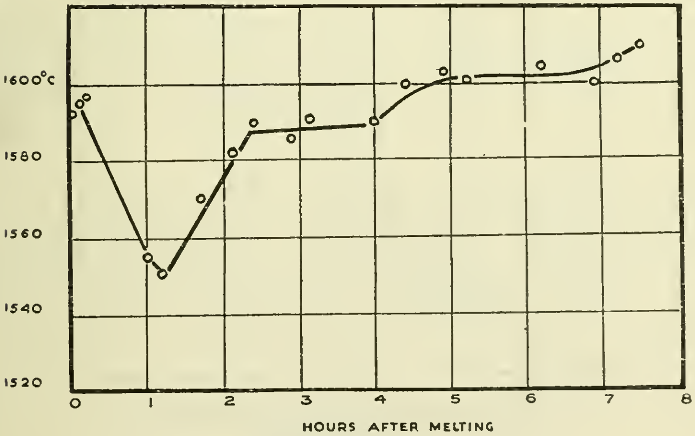

Fig. 10.

The higher the temperature the greater the velocity of reaction (3), and McCance has shown that an increase of 50° C. in the final temperature would cause a decrease of 33 per cent. in the FeO content of the finished steel.

Although in general slags of a given composition become more fluid the higher the temperature, this does not by any means hold when chemical reactions are taking place. Hence it is found that as the FeO is cleared from the steel, a corresponding diminution occurs in the slag with consequent thickening, unless another base such as lime is added.

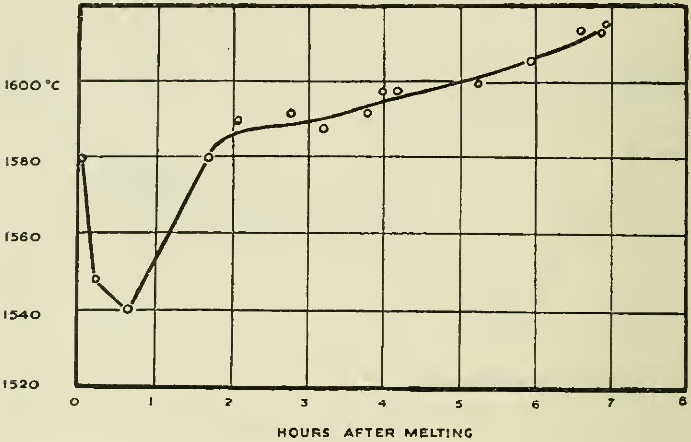

Fig. 11.

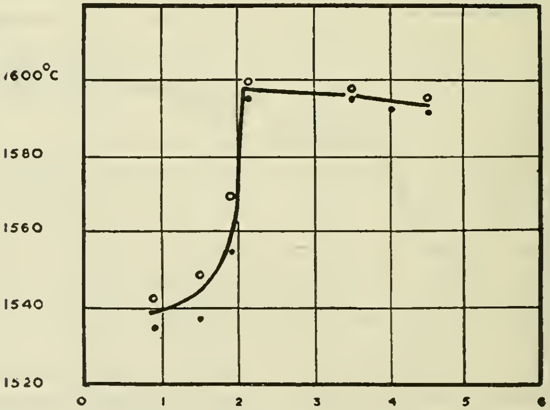

Fig. 12.—Temperature Curve for Dead Soft Basic Steel Charge.

It is a knowledge of the progress of these varied reactions which constitutes the factor covered by the term "condition." All the signs by which such progress can be judged—namely, viscosity and general appearance of the slag, appearance of the surface and fracture of spoon samples of metal, rate of evolution of CO and information regarding the temperature of the lower layers of slag and metal which the appearance of the bubbles can give—must be taken into account as well as the actual temperature. Again, in actual practice the thickness of the slag blanket, and also to some extent the composition of the charge, must be considered in connection with temperature control. The composition assumes an important aspect when appreciable quantities of silicon or manganese are present in the bath, for the oxidation of these yields considerable heat units.

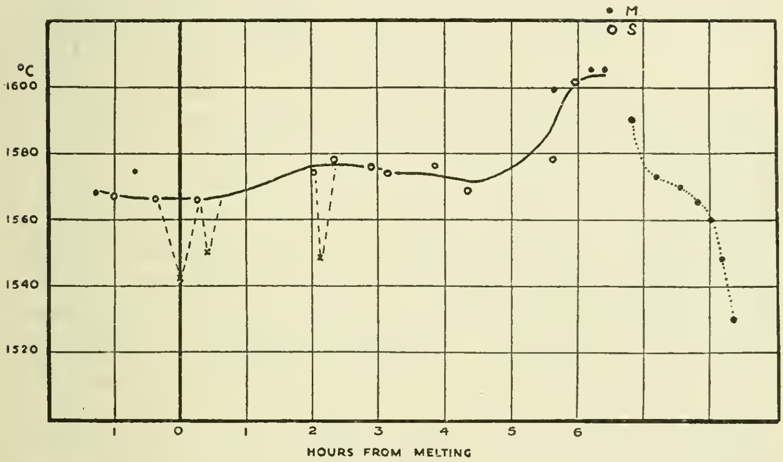

FIG. 13.

With regard to the final temperature attained, the following points must be taken into account :

(*a*) The amount and nature of the final additions.
(*b*) The solidification temperature of the steel.
(*c*) The method of casting.

This brings us to the second question—namely, the temperature considerations affecting the production of definite types of ingots. This latter covers such ingot characteristics as skin, position and size of blowholes, extent of pipe and major segregation, extent of columnar crystals and minor dendritic segregates, freedom from non-metallic inclusions, &c. The rôle of temperature as a governing factor of these characteristics is, however, largely obscured by the effect of varying the method of teeming. The possible combinations of ladle nozzle size and type with uphill and direct casting (the latter admitting of trough teeming as a further set of variables) is enormous. Only the main effects of temperature for a given pit setting can be outlined here.

Piping and Major Segregation.—Since, in general, liquids expand on heating, it follows that the higher the temperature of the steel at the time of casting the greater the volume of a given weight. Also as the solid crust forms almost immediately in the mould, the original volume of the steel defines the length of the ingot (assuming that the steel is in such a condition that it will set solid). If it be assumed that the coefficient of cubical expansion of liquid steel is similar to that for solid steel at high temperature, an approximate idea can be formed of the increased volume of pipe due to any given excess of temperature. The coefficient of cubical expansion of solid steel above 1000° C. can be taken as $7 \cdot 5 \times 10^{-5}$. Accepting this value, it can be calculated that for an increase of temperature of 50° C. an ingot measuring $15'' \times 15'' \times 60''$ would have an extra shrinkage of approximately $50 \cdot 6$ cubic inches. Whilst this is only a small percentage of the total volume, it might easily affect an appreciable volume of the ingot, especially in narrow end-up casting.

With regard to major segregation, this tends to be more accentuated the higher the temperature of the steel in the mould. As the steel sets from the outside, the higher the temperature of the remaining liquid the greater its solubility for impurities, and consequently the greater the ultimate concentration of impurities in the final portion to solidify at the base of the pipe.

Position of Blowholes.—Apart from the large cavities surrounding the pipe, and those found immediately under the skin of the ingot, the normal blowholes are due to the liberation of gas from solution during the course of solidification. At the moment of liberation of the gas the liquid steel is evidently saturated. It is most probable that temperature is an important factor in connection with the nature of the gases absorbed in the furnace. One often finds in certain types of ingot blowholes arranged in definite layers, and in such cases it seems obvious that different gases have been responsible for them, for the liquid steel has evidently become saturated with each one successively, thus giving rise to definite layers corresponding with the liberation of the respective gases. Besides this effect on the furnace reactions, which causes the absorption of various gases, the solubility of liquid steel for the same increases with the temperature, and consequently the hotter the steel the greater the amount of gas given up on solidification. This effect will tend to mask that mentioned in the previous paragraph.

Extent of Columnar Crystals and Minor Dendritic Segregates.—The normal ingot generally solidifies in four distinct stages, each having a characteristic macroscopic appearance. There is first a narrow zone of more or less equiaxed chill crystals, followed by a much thicker layer of columnar crystals, which may occupy a zone up to 20 per cent. of the radius in depth. This in turn is followed by equiaxed dendritic crystals much larger than those of the first layer, and finally the centre solidifies as cell crystals, exhibiting no dendritic structure, but surrounded by more or less continuous boundaries of material less pure than the cores. Keeping constant such factors as composition, dimensions, and temperature of mould, the hotter the metal filling the latter the more pronounced will be the first two types of crystallisation, and in the extreme the fourth or even the third (in certain nickel steels) type might be entirely absent. Also the more rapid the solidification the greater the departure from equilibrium of the solid and liquid phases. Hence the higher the initial temperature the more marked is the dendritic and intercrystalline segregation. The latter is particularly found separating columnar crystals, and at the junction of such growing from adjacent sides of the mould. In very pronounced cases these intercrystalline segregates are very weak and give rise to bursting or cracking in forging or rolling processes.

Non-Metallic Inclusions.—Provided that the steel has been thoroughly deoxidised, the hotter it is the greater is the chance of it becoming freed from inclusions in the ladle, for its viscosity will be less. With regard to the ingot, the advantage of high temperature in this connection is one which is governed largely by the method of casting. Certainly, the hotter the metal the longer it will remain fluid, and so the greater is the time available for the inclusions to rise into the pipe region; but on the other hand, the greater is the fluxing action on any refractories with which it comes in contact, especially during bottom teeming. Also, whilst high temperature in the mould is advantageous in freeing the steel from inclusions, it is decidedly detrimental with regard to the previous points raised.

CONCLUSION.

With this brief synopsis of the rôle of temperature in steel making and casting, this report concludes.

The author would like to take this opportunity of thanking the management of Messrs. Samuel Fox & Co., Ltd., for the facilities placed at his disposal, and for permission to publish the data contained in the Appendices, which form the basis for this report. His thanks are also due to the technical assistants, Messrs. A. P. Cadman and E. G. Pinder, who carried out the observations at the furnaces over a period of eight months.

APPENDIX I.

COMPARISON OF TEMPERATURES TAKEN IN FURNACES UNDER DIFFERENT CONDITIONS.

These observations were made by two assistants whose readings were checked each day by a third independent observer. The pyrometer was compared with the standard lamp on each shift. In taking observations the best conditions possible at the time would be utilised.

All the readings are as obtained from the pyrometer. Since they are all more or less in the same region of the scale, and the differences are the important feature, it has not been thought necessary to make the pyrometer correction (see p. 36).

Apart from this the tables are self-explanatory, and are summarised in the following pages.

U Furnace (*Acid*).

Observer A.						Observer B.					
Cast No.	Apparent Temperatures.					Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.		Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
905	1604	1558	46	1532	26	904	1640	1590	50	1556	34
	1616	1572	44	1548	24		1649	1600	49	1575	25
906	1612	1568	44	1532	36	906	1590	1530	60	1499	31
	1628	1584	44	1556	28	915	1590	1549	41	1515	34
914	1552	1518	34	1488	30	920	1553	1510	43	1480	30
924	1554	1518	36	1496	22	932	1570	1529	41	1500	29
926	1584	1538	46	1514	24		1615	1575	40	1542	33
885	1562	1518	44	1488	30		1620	1589	31	1552	37
	1568	1535	33	1514	21	935	1580	1530	50	1500	30
887	1590	1548	42	1524	24		1565	1538	27	1505	33
	1610	1558	52	1534	24		1599	1549	50	1515	34
889	1554	1514	40	1496	18		1610	1565	45	1530	35
	1608	1568	40	1548	20	936	1545	1500	45	1469	31
890	1572	1528	44	1502	26		1590	1549	41	1515	34
	1584	1558	26	1534	24		1610	1570	40	1540	30
	1602	1558	44	1534	24		1629	1585	44	1552	33
891	1566	1522	44	1502	20		1630	1589	41	1549	40
	1582	1538	44	1516	22	938	1612	1560	52	1529	31
	1622	1584	38	1558	26		1600	1560	40	1530	30
893	1582	1546	36	1522	24		1615	1580	35	1539	41
	1598	1552	46	1526	26		1625	1582	43	1550	32
	1612	1568	44	1542	26		1615	1575	40	1540	35
895	1542	1498	44	1474	24	939	1552	1515	37	1490	25
	1596	1552	44	1534	18		1599	1559	40	1525	34
	1614	1572	42	1548	24		1632	1590	42	1549	41
897	1548	1504	44	1478	26		1635	1595	40	1550	45
899	1552	1508	44	1476	32	941	1525	1490	35	1460	30
	1574	1528	46	1502	26		1545	1505	40	1470	35
	1598	1542	56	1522	20		1569	1530	39	1499	31
901	1538	1492	46	1472	20		1585	1540	45	1509	31
	1540	1512	28	1492	20		1650	1595	55	1560	35
	1602	1558	44	1534	24	943	1552	1510	42	1479	31
903	1544	1510	34	1482	28		1589	1540	49	1500	40
	1578	1538	40	1514	24		1649	1600	49	1549	51
	1614	1578	36	1554	24	945	1545	1500	45	1460	40
871	1564	1522	42	1498	24		1550	1510	40	1479	31
879	1554	1518	36	1494	24		1572	1530	42	1500	30
933	1546	1510	36	1474	36		1679	1620	59	1582	38
	1604	1558	46	1532	26		1650	1589	61	1550	39
934	1542	1498	44	1470	28	947	1549	1504	45	1472	32
	1582	1540	42	1508	32		1572	1529	43	1490	39
	1626	1588	38	1556	32		1589	1540	49	1500	40
937	1638	1594	44	1572	22		1630	1580	50	1549	31
940	1558	1514	44	1482	32	948	1529	1490	39	1465	25
	1588	1534	54	1512	22		1555	1510	45	1485	25
	1638	1578	60	1552	26		1629	1585	44	1540	45
Average			42	...	25	Average			44	...	34
Minimum			26	...	18	Minimum			27	...	25
Maximum			60	...	36	Maximum			61	...	51

V Furnace (*Acid*).

OBSERVER B.

Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
3734	1560	1520	40	1495	25
	1572	1530	42	1500	30
	1623	1575	48	1540	35
	1630	1589	41	1539	50
	1628	1585	43	1550	35
3742	1640	1590	50	1552	38
	1645	1598	47	1575	23
3744	1550	1510	40	1470	40
3745	1559	1520	39	1490	30
	1568	1525	43	1490	35
	1576	1539	37	1500	39
	1595	1560	35	1528	32
	1598	1555	43	1519	36
	1630	1578	52	1530	48
	1630	1595	35	1550	45
3751	1599	1559	40	1520	39
3753	1550	1510	40	1470	40
	1580	1542	38	1510	32
	1589	1555	34	1521	34
3755	1535	1499	36	1468	31
3761	1565	1529	36	1498	31
	1575	1539	36	1502	37
3762	1610	1580	30	1542	38
3768	1572	1530	42	1490	40
	1622	1579	43	1529	50
	1620	1589	31	1550	39
	1630	1590	40	1550	40
	1632	1589	43	1556	33
3769	1600	1559	41	1520	39
	1605	1560	45	1522	38
	1630	1589	41	1540	49
3778	1545	1502	43	1490	12
	1560	1520	40	1490	30
	1565	1525	40	1499	26
3780	1636	1595	41	1560	35
	1630	1590	40	1550	40
3786	1540	1500	40	1472	28
	1620	1580	40	1540	40
3790	1566	1519	47	1480	39
	1570	1526	44	1495	31
	1580	1535	45	1509	26
3803	1630	1589	41	1545	44
	1635	1590	45	1550	40
3805	1560	1520	40	1485	35
	1568	1530	38	1500	30
	1625	1580	45	1545	35
Average .	. .	. .	41	...	36
Minimum .	. .	. .	30	...	12
Maximum .	. .	. .	52	...	50

W Furnace (Acid).

Observer A.						Observer B.					
Cast No.	Apparent Temperatures.					Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.		Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
1075	1598	1550	48	1520	30	1109	1612	1579	33	1535	44
1083	1562	1528	34	1510	18		1600	1559	41	1520	39
1089	1550	1508	42	1486	22	1113	1610	1570	40	1523	47
1092	1652	1600	52	1578	22	1115	1670	1650	20	1605	45
1095	1552	1496	56	1474	22	1117	1575	1515	60	1489	26
	1577	1535	42	1508	27	1120	1641	1600	41	1569	31
1096	1544	1498	46	1472	26	1122	1640	1590	50	1546	44
	1598	1552	46	1528	24	1125	1574	1535	39	1500	35
	1628	1582	46	1552	30		1634	1599	35	1565	34
	1652	1608	44	1564	44		1599	1555	44	1515	40
1098	1566	1512	54	1490	22	1134	1600	1569	31	1540	29
	1578	1532	46	1504	28		1590	1555	35	1529	26
	1608	1560	48	1532	28		1590	1550	40	1520	30
1100	1598	1552	46	1528	24		1600	1560	40	1529	31
	1620	1578	42	1546	32		1595	1559	36	1525	34
	1646	1600	46	1562	38	1135	1588	1540	48	1506	34
	1656	1612	44	1578	34		1572	1530	42	1500	30
	1660	1616	44	1584	32		1620	1580	40	1550	30
1102	1568	1522	46	1500	22		1639	1590	49	1552	38
	1594	1548	46	1518	30	1137	1560	1515	45	1490	25
	1612	1562	50	1538	24		1582	1540	42	1512	28
	1648	1598	50	1562	36		1610	1579	31	1545	34
1104	1546	1510	36	1486	24		1645	1599	46	1575	24
	1596	1558	38	1530	28	1139	1542	1499	43	1465	34
1106	1544	1512	32	1486	26		1546	1506	40	1485	21
	1582	1538	44	1516	22		1585	1540	45	1509	31
	1604	1568	36	1538	30		1590	1549	41	1500	49
1133	1548	1512	36	1478	34		1649	1589	60	1545	44
	1596	1548	48	1520	28	1140	1625	1580	45	1563	17
1136	1566	1524	42	1498	26		1625	1585	40	1539	46
	1594	1548	46	1518	30	1141	1559	1520	39	1469	51
	1622	1578	44	1552	26		1586	1526	60	1500	26
1138	1556	1518	38	1488	30		1575	1539	36	1505	34
	1584	1542	42	1520	22		1668	1622	46	1592	30
	1622	1581	41	1554	27	1142	1555	1510	45	1479	31
1143	1552	1510	42	1486	24		1585	1539	46	1500	39
	1608	1564	44	1530	34	1144	1525	1480	45	1455	25
	1654	1606	48	1584	22		1570	1529	41	1495	34
1145	1574	1532	42	1514	18		1590	1555	35	1520	35
	1608	1564	44	1530	34		1600	1560	40	1529	31
	1642	1594	48	1570	24		1646	1590	56	1556	34
1147	1584	1538	46	1508	30	1146	1555	1520	35	1495	25
	1644	1594	50	1572	22		1625	1575	50	1535	40
1149	1596	1548	48	1522	26	1148	1532	1500	32	1470	30
	1618	1574	44	1548	26		1569	1520	49	1492	28
	1648	1606	42	1578	28		1582	1540	42	1512	28
Average	.	.	44	...	27	Average	.	.	42	...	34
Minimum	.	.	32	...	18	Minimum	.	.	20	...	17
Maximum	.	.	54	...	44	Maximum	.	.	60	...	51

X Furnace (*Basic*).

OBSERVER A. OBSERVER B.

Cast No.	Apparent Temperatures.					Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.		Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
1292	1602	1554	48	1528	26	1294	1620	1580	40	1548	32
	1618	1584	34	1552	32		1630	1590	40	1549	41
1293	1630	1580	50	1544	36	1297	1636	1590	46	1560	30
1295	1600	1548	52	1518	30		1620	1579	41	1542	37
	1622	1578	44	1542	36	1299	1542	1500	42	1460	40
1296	1612	1572	40	1536	36		1570	1530	40	1495	35
	1616	1566	50	1522	44		1620	1579	41	1540	39
1298	1590	1554	36	1532	22	1302	1583	1540	43	1500	40
	1606	1570	36	1552	18		1629	1590	39	1546	44
1300	1600	1542	58	1524	18		1655	1589	66	1555	34
	1612	1562	50	1526	36		1650	1595	55	1585	10
1301	1604	1574	30	1542	32	1303	1594	1550	44	1526	24
	1618	1576	42	1544	32		1609	1550	59	1515	35
1304	1588	1544	44	1510	34		1630	1589	41	1554	35
	1592	1558	34	1524	34		1635	1595	40	1549	46
	1596	1560	36	1532	28	1305	1585	1540	45	1505	35
1307	1594	1560	34	1532	28		1599	1560	39	1520	40
	1588	1552	36	1528	24		1600	1560	40	1528	32
1309	1584	1532	52	1514	18	1306	1570	1528	42	1495	33
	1598	1552	46	1520	32		1589	1540	49	1505	35
1310	1624	1578	46	1552	26		1630	1585	45	1549	36
1312	1584	1538	46	1512	26	1308	1539	1500	39	1465	35
	1614	1562	52	1530	32		1620	1585	35	1546	39
	1614	1564	50	1522	42	1310	1560	1519	41	1490	29
1313	1596	1542	54	1518	24		1569	1525	44	1490	35
	1612	1558	54	1526	32		1590	1549	41	1517	32
	1616	1568	48	1544	24	1311	1539	1500	39	1469	31
1315	1594	1542	52	1518	24		1560	1520	40	1487	33
	1610	1558	52	1524	34		1579	1529	50	1495	34
1316	1590	1552	38	1518	34		1600	1559	41	1520	39
	1604	1572	32	1548	24		1600	1560	40	1525	35
	1626	1584	42	1554	30		1610	1565	45	1536	29
1318	1596	1542	54	1520	22	1313	1580	1530	50	1505	25
1319	1610	1546	64	1520	26	1317	1550	1515	35	1477	38
	1612	1552	60	1524	28		1570	1529	41	1500	29
	1622	1584	38	1552	32		1590	1556	34	1536	20
1321	1578	1536	42	1516	20	1320	1570	1530	40	1500	30
	1598	1552	46	1520	32		1642	1600	42	1566	34
	1616	1564	52	1530	34	1322	1552	1510	42	1490	20
	1626	1578	48	1548	30		1570	1529	41	1506	23
1324	1612	1562	50	1532	30		1610	1579	31	1546	33
	1624	1574	50	1538	36	1323	1620	1585	35	1548	37
1326	1612	1558	54	1522	36	1325	1590	1550	40	1530	20
	1634	1582	52	1544	38						
1329	1566	1532	34	1506	26						
Average	.	.	46	...	30	Average	.	.	42	...	33
Minimum	.	.	30	...	18	Minimum	.	.	31	...	10
Maximum	.	.	64	...	44	Maximum	.	.	66	...	46

Y Furnace (Basic).

OBSERVER A. OBSERVER B.

Cast No.	Apparent Temperatures.					Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.		Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
80	1598	1552	46	1530	22	111	1616	1560	56	1520	40
83	1582	1548	34	1522	26	114	1643	1590	53	1535	55
84	1550	1510	40	1485	25	117	1630	1590	40	1548	42
96	1538	1498	40	1476	22	132	1542	1500	42	1470	30
	1620	1582	38	1556	26		1590	1545	45	1510	35
98	1554	1498	56	1474	24		1610	1559	51	1524	35
	1630	1584	46	1552	32		1594	1550	44	1520	30
100	1568	1518	50	1501	17	133	1559	1510	49	1470	40
101	1552	1498	54	1472	26		1575	1530	45	1495	35
	1604	1556	48	1528	28		1575	1541	34	1510	31
103	1558	1512	46	1484	28		1615	1560	55	1520	40
	1582	1538	44	1514	24		1615	1570	45	1535	35
	1604	1560	44	1536	24	135	1595	1550	45	1510	40
113	1552	1518	34	1472	46		1615	1570	45	1540	30
	1632	1588	44	1560	28		1680	1629	51	1580	49
112	1548	1514	34	1482	32		1690	1650	40	1610	40
116	1604	1560	44	1534	26	130	1620	1570	50	1532	38
	1618	1572	46	1548	24		1600	1575	25	1520	55
	1645	1604	41	1568	36		1585	1550	35	1530	20
105	1552	1498	54	1470	28	129	1593	1545	48	1515	30
	1584	1538	46	1516	22		1620	1570	50	1539	31
106	1544	1498	46	1474	24	128	1599	1560	39	1530	30
	1592	1544	48	1518	26		1629	1585	44	1549	36
	1618	1575	43	1534	41		1610	1575	35	1540	35
110	1522	1488	34	1468	20	123	1580	1532	48	1510	22
	1534	1498	36	1474	24		1610	1575	35	1535	40
	1608	1564	44	1528	36	169	1560	1528	32	1485	43
131	1562	1522	40	1498	24		1600	1565	35	1536	29
	1586	1558	28	1532	26		1610	1569	41	1535	34
138	1546	1512	34	1472	40		1605	1570	35	1539	31
	1608	1568	40	1532	36	170	1542	1500	42	1465	35
	1626	1584	42	1564	20		1562	1520	42	1470	50
127	1548	1516	32	1474	42		1600	1569	31	1528	41
	1584	1542	42	1518	24		1610	1570	40	1539	31
	1632	1588	44	1556	32		1610	1576	34	1540	36
125	1558	1518	40	1472	46	175	1610	1585	25	1545	40
	1584	1538	46	1512	26		1650	1590	60	1558	32
	1614	1568	46	1532	36		1635	1599	36	1585	14
	1622	1578	44	1552	26	176	1555	1525	30	1490	35
124	1546	1512	34	1472	40		1550	1520	30	1490	30
	1576	1548	28	1522	26		1570	1530	40	1500	30
	1624	1582	42	1554	28	180	1600	1560	40	1530	30
	1636	1594	42	1568	26		1612	1570	42	1539	31
168	1604	1554	50	1526	28		1630	1585	45	1550	35
	1616	1558	58	1526	32		1629	1585	44	1555	30
	1608	1566	42	1528	38	181	1562	1520	42	1487	33
							1575	1530	45	1506	30
Average	.	.	43	...	29	Average	.	.	42	...	35
Minimum	.	.	28	...	17	Minimum	.	.	25	...	14
Maximum	.	.	58	...	46	Maximum	.	.	60	...	55

Z Furnace (*Basic*).

Observer B.

Cast No.	Apparent Temperatures.				
	Gas.	Slag Gas On.	D_1.	Slag Gas Off.	D_2.
1	1554	1512	42	1490	22
4	1569	1520	49	1485	35
	1569	1525	44	1492	33
	1620	1580	40	1542	38
3	1550	1509	41	1460	49
	1570	1529	41	1500	29
7	1555	1510	45	1480	30
	1582	1540	42	1502	38
	1590	1548	42	1508	40
	1606	1560	46	1524	36
11	1542	1510	32	1460	50
	1565	1528	37	1492	36
	1598	1560	38	1520	40
14	1570	1509	61	1460	49
	1585	1535	50	1502	33
15	1620	1570	50	1535	35
16	1580	1540	40	1501	39
	1630	1570	60	1532	38
17	1600	1559	41	1519	40
	1605	1585	20	1540	45
18	1539	1500	39	1470	30
20	1550	1515	35	1480	35
	1580	1539	41	1510	29
	1554	1509	45	1480	29
26	1580	1530	50	1500	30
	1628	1590	38	1548	42
29	1530	1490	40	1460	30
	1640	1570	70	1535	35
	1645	1578	67	1537	41
32	1580	1535	45	1510	25
	1600	1556	44	1520	36
33	1570	1539	31	1502	37
	1579	1540	39	1505	35
	1610	1560	50	1530	30
	1620	1585	35	1545	40
34	1560	1529	31	1500	29
	1610	1572	38	1540	32
36	1588	1549	39	1505	44
	1599	1560	39	1524	36
39	1580	1540	40	1503	37
40	1575	1530	45	1500	30
	1625	1580	45	1544	36
	1630	1589	41	1550	39
Average			43	...	36
Minimum			20	...	22
Maximum			70	...	50

APPENDIX II.

Comparison of Last Temperatures taken in Furnace before Tapping, with those taken during Tapping.

These records were obtained at the same time as those given in Appendix I.

In this case the pyrometer readings given as "apparent temperatures" have been corrected by the curve shown in Fig. 5. The affixes used are: C = Commencement and F = Final, and they refer to the molten metal and slag from the furnace. .

Unless otherwise stated, the time elapsing between the last temperature in the furnace and the first during tapping, is not greater than ten minutes. The readings on the slag stream were not continued until all was out owing to the taking of teeming temperatures. In most cases observations were discontinued when slag had been flowing for three minutes. This may not be sufficient to get a true idea of the surface slag temperature in cases where there is a heavy slag blanket and a big temperature gradient. In no case, however, has a greater difference than 20° C. been observed whilst slag was flowing.

The true temperature of the metal has been obtained by using the value 0·40 for the emissivity of liquid steel.

In order to simplify matters in calculating the emissivities of the slags, a series of curves were drawn connecting the difference between true and observed temperatures with emissivity. Since the technical observations made do not warrant a greater accuracy than two significant figures in the emissivity value, this method gives a sufficient approximation. The curves were drawn from interpolated values taken from Table IV. of the report of the Pyrometer Committee of the American Research Council (*loc. cit.*). These values are tabulated below:

Observed Temperature.	Difference between True and Observed Temperatures.	Emissivity.	Observed Temperature.	Difference between True and Observed Temperatures.	Emissivity.
1475	50·5	0·70	1500	52	0·70
	61	0·65		63	0·65
	73	0·60		75	0·60
	87	0·55		89	0·55
	101	0·50		104	0·50
	115	0·45			

Observed Temperature.	Difference between True and Observed Temperatures.	Emissivity.	Observed Temperature.	Difference between True and Observed Temperatures.	Emissivity.
1525	53·5	0·70	1550	67	0·65
	65	0·65		80	0·60
	78	0·60		94	0·55
	92	0·55		110	0·50
	107	0·50			

V Furnace (Acid).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			True Temp. Metal (a).	Emissivity Slag (x).	Correct Temp. of Slag(F) (a').	Last Temp. in Furnace (b).	a'–b.
		Metal (F).	Slag (C).	Slag (F).					
3796	0·30–0·40	1497	1541	1546	1638	0·54	1643	1598	45
3811		1477	1526	1522	1614	0·56	1610	1591*	19
3812		1477	1524	1526	1614	0·56	1616	1584*	32
3813		1479	1505	1497	1617	0·48	1609	1569*	40
3834	0·40–0·60	1489	1533	1542	1628	0·54	1637	1594*	43
3832		1485	1537	1540	1625	0·57	1628	1587*	41
3831		1482	1528	1535	1620	0·55	1627	1595*	32
3826		1482	1504	1513	1620	0·46	1629	1597*	32
3824		1480	1539	1542	1618	0·60	1621	1598*	23
3933		1476	1539	1526	1613	0·61	1600	1572*	28
3734		1493	1535	1542	1633	0·53	1640	1594*	46
3750		1472	1509	1515	1609	0·52	1615	1587*	28
3760		1464	1499	1503	1599	0·51	1603	1572*	31
3761		1487	1537	1527	1626	0·56	1616	1601*	15
3769		1483	1528	1532	1621	0·55	1625	1579*	46
3780		1486	1520	1520	1625	0·50	1625	1587*	38
3786		1483	1527	1533	1621	0·55	1627	1572	55
3789		1485	1533	1528	1625	0·55	1620	1587*	33
3790		1476	1505	1513	1613	0·49	1621	1570*	51
3795		1468	1515	1518	1604	0·56	1607	1591*	16
3801		1467	1518	1522	1603	0·57	1607	1591*	16
3803		1482	1513	1531	1620	0·50	1638	1572	66
3805		1479	1505	1520	1617	0·47	1637	1582	55
3821		1477	1524	1528	1614	0·55	1618	1569*	49
3823		1488	1528	1539	1627	0·53	1638	1592*	46
3744	CrNi	1468	1517	1513	1604	0·56	1600	1581*	19
3745	0·3–0·4	1482	1505	1509	1620	0·46	1624	1572	52
3753		1491	1540	1542	1631	0·56	1633	1579*	54
3755		1483	1513	1517	1621	0·49	1625	1579*	46
3742	CrV	1476	1501	1497	1613	0·47	1609	1579*	30
3759	0·3–0·4	1467	1533	1525	1603	0·63	1595	1596*	(0)
3797		1497	1546	1552	1638	0·56	1644	1599*	45
Average						0·54	1621	1584	37
Minimum						0·46	...	...	15
Maximum						0·63	...	...	66

Temperatures in column (b) marked * were taken with gas on, and have been corrected to "gas off" temperatures.

W Furnace (Acid).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			True Temp. Metal (*a*).	Emissivity Slag (*x*).	Correct Temp. of Slag (F) (*a'*).	Last Temp. in Furnace (*b*).	*a'*–*b*.
		Metal (F).	Slag (C).	Slag (F).					
1196	0·30–0·40	1458	1507	1509	1592	0·56	1594	1572	22
1208		1492	1423	1526	1632	0·50	1635	1596*	39
1209		1483	1531	1545	1621	0·56	1635	1573	62
1218		1477	1515	1524	1614	0·52	1623	1592	31
1219		1471	1513	1518	1608	0·53	1613	1572	41
1224		1482	1505	1515	1620	0·47	1630	1580*	50
1243		1469	1512	1515	1605	0·54	1608	1595*	13
1244		1466	1513	1515	1601	0·56	1603	1595*	8
1192	0·40–0·60	1460	1512	1512	1595	0·57	1595	1572	23
1193		1454	1496	1494	1588	0·54	1586	1560	26
1194		1452	1490	1498	1585	0·53	1593	1562	31
1197		1474	1531	1531	1611	0·59	1611	1577*	34
1198		1458	1504	1500	1592	0·55	1588	1574	14
1199		1460	1496	1502	1595	0·51	1601	1564*	37
1200		1464	1502	1505	1599	0·52	1603	1573	30
1201		1471	1536	1540	1608	0·62	1612	1587	25
1203		1467	1491	1492	1603	0·47	1604	1567	37
1207		1484	1523	1531	1622	0·52	1630	1574	56
1213		1469	1509	1517	1605	0·52	1614	1566*	48
1214		1469	1502	1501	1605	0·50	1604	1554	50
1286		1486	1528	1541	1625	0·53	1638	1592*	46
1295		1474	1503	1509	1611	0·49	1617	1587*	30
1296		1460	1505	1509	1595	0·55	1599	1577*	22
1297		1472	1509	1511	1609	0·51	1611	1594*	17
1191	Over 1%	1477	1523	1527	1614	0·55	1618	1580	38
1212		1450	1471	1468	1583	0·46	1580	1543*	37
1221		1479	1496	1505	1617	0·45	1626	1554	72
1231		1464	1505	1509	1599	0·53	1603	1570*	33
1234		1460	1487	1496	1595	0·48	1604	1572*	32
1233		1458	1496	1502	1592	0·52	1598	1568*	30
1240		1443	1489	1494	1575	0·56	1580	1544	36
1255		1445	1500	1503	1577	0·59	1580	1553*	27
1204	CrNi	1480	1531	1527	1618	0·57	1614	1574	40
1205	0·3–0·4%C.	1484	1524	1531	1623	0·53	1630	1565	65
1239		1477	1531	1540	1614	0·58	1623	1580*	43
1210	CrV.	1507	1553	1557	1650	0·54	1654	1601*	53
1215	0·3–0·4%C.	1464	1494	1505	1599	0·49	1610	1572*	38
1225		1482	1526	1531	1620	0·54	1625	1583*	42
1227		1478	1505	1505	1616	0·48	1616	1580*	36
1248		1487	1512	1521	1626	0·47	1635	1608	27
1249		1487	1540	1549	1626	0·57	1635	1586*	49
Average						0·53	1611	1575	36
Minimum						0·45	...	...	8
Maximum						0·62	...	...	72

Temperatures in column (*b*) marked * were taken with gas on, and have been corrected to "gas off" temperatures.

X Furnace (*Basic*).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			True Temp. Metal (*a*).	Emissivity Slag (*x*).	Correct Temp. of Slag(F) (*a′*).	Last Temp. in Furnace (*b*).	*a′–b*.
		Metal (F).	Slag (C).	Slag (F).					
1330	0·10–0·20	1473	1510	1508	1610	0·51	1608	1572	36
1331		1468	1515	1523	1604	0·56	1612	1572	40
1332		1450	1496	1502	1583	0·55	1589	1572	17
1333		1433	1466	1469	1563	0·51	1566	1546*	20
1335		1452	1498	1505	1585	0·55	1592	1550	42
1336		1470	1521	1526	1606	0·57	1611	1584	27
1338		1473	1523	1531	1610	0·56	1618	1571	47
1343		1518	1550	1562	1662	0·50	1674	1595	79
1348		1435	1469	1477	1565	0·51	1573	1541*	32
1351		1454	1494	1502	1587	0·54	1595	1556*	39
1353		1457	1497	1509	1591	0·53	1603	1569	34
1354		1466	1507	1512	1601	0·53	1606	1574	32
1390		1475	1521	1528	1612	0·55	1619	1587*	32
1395		1458	1504	1531	1592	0·55	1619	1562*	57
1397		1452	1513	1518	1585	0·62	1590	1563	27
1398		1468	1505	1513	1604	0·52	1612	1575*	37
1399		1466	1524	1521	1601	0·60	1598	1567*	31
1401		1469	1509	1521	1605	0·53	1617	1572*	45
1402		1470	1523	1529	1606	0·58	1612	1580*	32
1406		1473	1528	1533	1610	0·59	1615	1594*	21
1339	0·20–0·60	1488	1523	1535	1627	0·51	1639	1572	67
1340		1470	1531	1535	1606	0·61	1610	1571	39
1346		1454	1496	1498	1588	0·54	1590	1565	25
1345		1456	1513	1509	1590	0·60	1586	1572*	14
1347		1467	1531	1533	1603	0·62	1605	1571	34
1349		1458	1500	1500	1592	0·54	1592	1572*	20
1355		1459	1496	1491	1593	0·52	1588	1567*	21
1370		1446	1490	1494	1578	0·55	1582	1560*	22
1369		1462	1513	1531	1597	0·57	1615	1572	33
1377		1458	1507	1510	1592	0·56	1595	1560*	35
1390		1463	1518	1523	1598	0·59	1603	1567	36
1391		1452	1498	1492	1585	0·55	1579	1568*	11
1337	0·60–1·0	1466	1540	1533	1601	0·67	1594	1570	24
1361		1452	1512	1503	1585	0·61	1576	1572*	(4)
1364		1456	1485	1490	1590	0·49	1595	1560*	35
1368		1450	1496	1500	1583	0·55	1587	1557*	30
1372		1460	1506	1513	1594	0·55	1601	1570*	31
1383		1465	1505	1518	1600	0·53	1613	1561	52
1389		1450	1504	1528	1583	0·59	1591	1562	29
1392		1443	1487	1495	1575	0·55	1583	1560	23
1394		1464	1505	1519	1599	0·53	1613	1566	47
1407		1461	1503	1510	1596	0·53	1603	1580*	23
Average						0·56	1600	1567	33
Minimum						0·49	...	...	11
Maximum						0·67	...	...	79

Temperatures in column (*b*) marked * were taken with gas on, and have been corrected to "gas off" temperatures.

Y Furnace (*Basic*).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			True Temp. Metal (*a*).	Emissivity Slag (*x*).	Correct Temp. of Slag (F) (*a′*).	Last Temp. in Furnace (*b*).	*a′*–*b*.
		Metal (F).	Slag (C).	Slag (F).					
190	0·10–0·20	1463	1513	1527	1598	0·57	1612	1594*	18
211		1443	1486	1485	1573	0·55	1572	1549′	23
215		1469	1513	1531	1605	0·55	1623	1565	58
223		1466	1507	1510	1601	0·54	1604	1575*	29
227		1471	1531	1549	1608	0·60	1626	1572	54
228		1474	1531	1540	1611	0·59	1620	1568	52
172		1456	1502	1507	1590	0·55	1595	1566′	29
167		1460	1523	1528	1595	0·62	1600	1571	29
189	0·20–0·50	1470	1517	1524	1606	0·56	1613	1570	43
191		1456	1507	1510	1590	0·57	1593	1570	23
192		1458	1505	1515	1592	0·56	1602	1565	37
193		1452	1503	1503	1585	0·57	1585	1565′	20
194		1466	1513	1509	1601	0·56	1597	1573*	24
196		1454	1494	1502	1588	0·53	1596	1559′	37
197		1452	1498	1494	1585	0·55	1581	1553	28
203		1460	1505	1511	1595	0·55	1601	1561	40
206		1450	1509	1513	1583	0·61	1587	1562′	25
212		1445	1487	1495	1578	0·54	1586	1560	26
226		1466	1512	1521	1601	0·55	1610	1585*	25
232		1465	1523	1540	1600	0·60	1617	1580*	37
233		1456	1496	1503	1590	0·53	1597	1577*	20
195	0·50–0·80	1463	1523	1549	1598	0·61	1624	1577	47
198		1443	1513	1509	1575	0·67	1571	1572	(0)
199		1465	1523	1525	1600	0·60	1602	1562	40
201		1465	1518	1523	1600	0·58	1605	1572	33
204		1458	1498	1511	1592	0·53	1605	1573	32
205		1435	1485	1489	1565	0·58	1569	1557	12
209		1460	1513	1516	1595	0·58	1598	1572	26
214		1433	1452	1454	1563	0·45	1565	1537	28
217		1458	1507	1511	1592	0·57	1596	1566*	30
216		1455	1531	1554	1589	0·68	1612	1567	45
218		1450	1487	1492	1583	0·52	1588	1560*	28
221		1463	1521	1526	1598	0·60	1603	1569*	34
224		1457	1505	1523	1591	0·56	1609	1568*	41
178		1459	1509	1511	1593	0·57	1595	1560′	35
Average						0·58	1599	1568	31
Minimum						0·45	...	...	12
Maximum						0·68	...	...	58

Temperatures in column (*b*) marked ′ were obtained about fifteen to twenty minutes before tapping, and are therefore not strictly comparable with those in column (*a′*); those marked * were taken with gas on, and have been corrected to "gas off" temperatures.

Z Furnace (Basic).

Cast No.	Per Cent. Carbon.	Apparent Temperatures.			True Temp. Metal (a).	Emissivity Slag (x).	Correct Temp. of Slag (F) (a').	Last Temp. in Furnace (b).	$a'-b$.
		Metal (F).	Slag (C).	Slag (F).					
5	0·10–0·20	1458	1503	1507	1592	0·55	1596	1565*	31
6		1474	1508	1511	1611	0·50	1614	1593*	21
7		1463	1520	1524	1598	0·60	1602	1581*	21
13		1448	1487	1494	1580	0·53	1587	1555*	32
17		1486	1528	1546	1625	0·53	1646	1583	63
18		1463	1497	1520	1598	0·51	1624	1558	66
20		1466	1505	1524	1601	0·53	1622	1565	57
21		1470	1528	1535	1606	0·60	1613	1575*	38
22		1472	1503	1510	1609	0·49	1616	1587*	29
25		1491	1530	1532	1631	0·52	1633	1587*	46
27		1487	1534	1530	1626	0·56	1622	1591*	31
30		1456	1518	1515	1590	0·62	1587	1581*	(6)
31		1454	1508	1507	1588	0·58	1587	1562*	25
33		1468	1520	1532	1604	0·57	1616	1569	47
37		1476	1531	1535	1613	0·59	1617	1581*	36
35		1478	1530	1535	1616	0·57	1621	1585*	36
2	0·40–0·80	1463	1505	1504	1598	0·54	1597	1580*	17
3		1451	1505	1508	1584	0·59	1587	1561*	26
4		1475	1528	1534	1612	0·58	1618	1585*	33
8		1456	1499	1500	1590	0·54	1591	1566*	25
9		1458	1500	1505	1592	0·54	1597	1568*	29
10		1452	1502	1507	1585	0·57	1590	1570*	20
11		1464	1513	1516	1599	0·57	1602	1563*	39
14		1464	1497	1485	1599	0·50	1587	1556*	31
16		1472	1517	1516	1609	0·55	1608	1570*	38
19		1454	1489	1495	1588	0·51	1594	1565*	29
23		1454	1487	1491	1588	0·50	1592	1561*	31
24		1469	1528	1533	1605	0·60	1610	1574*	36
26		1463	1513	1524	1598	0·57	1609	1570*	39
29		1468	1528	1542	1604	0·61	1618	1671*′	47
32		1463	1497	1517	1598	0·51	1618	1570*′	48
34		1459	1505	1505	1593	0·55	1593	1565	28
36		1468	1528	1535	1604	0·61	1611	1565	46
39		1464	1520	1520	1599	0·59	1599	1607*	(–8)
40		1480	1520	1542	1618	0·53	1642	1585*	57
41		1458	1508	1515	1592	0·57	1609	1568*	41
Average						0·55	1610	1574	36
Minimum						0·49	...	...	17
Maximum						0·62	...	...	66

Temperatures marked ′ were obtained twenty minutes before tapping, and are therefore not strictly comparable with those in column (a'); those marked * were taken with gas on, and have been corrected to "gas off" temperatures.

Carnegie Scholarship Memoirs, 1923.]

Iron and Steel Institute.

AN INVESTIGATION OF THE BEHAVIOUR OF CERTAIN STEELS UNDER IMPACT AT DIFFERENT TEMPERATURES.

By F. C. LANGENBERG (Watertown Arsenal, U.S.A.)

The impact test being now practically in universal use, and having indeed almost been standardised, the time is appropriate to discuss the real significance of this test as applied in the present investigation.

The essential result obtained from the test is the amount of energy absorbed by a specimen while undergoing rupture or a certain deformation, regardless of the type of impact testing machine employed, or the form of specimen adopted. Attempts to correlate the impact test, particularly the notched-bar impact test, with other tests have frequently been made, and since the customary tension test has been very widely used as an accepted basis of engineering material, it is natural that considerable attention would be given to the discovery of a relationship between the tension test and the notched-bar impact test.

It is obvious that in drawing comparisons between static and dynamic tests the same essential data must be recorded in both cases. In the ordinary tension test as conducted to-day certain essential data are not recorded, and it is therefore impossible to deduce a definite relationship between the values usually recorded in the tension test and the data obtained from the impact test. In the ordinary tension test there are recorded : the elastic limit, the ultimate strength, the total elongation over a specified gauge length, and the reduction in area of cross-section. It is impossible to determine from these data the fibre stress at any given elongation after the elastic limit has been exceeded, and consequently the development of a complete stress-strain curve is impossible. To ascertain the amount of work absorbed by a tension specimen undergoing test, it is necessary to have available the complete stress-strain curve in order that the area under this curve may be ascertained. Although appliances for the recording of these data are available, they are not extensively used in commercial testing. An impact test reveals directly the amount of work which must be absorbed by a given specimen in order to produce rupture or a certain deformation, but the maximum fibre stress is not ascertained. In the usual tension test, assuming that the test is representative of the material, the engineer can, if the elastic limit has been determined, apply the result in calculating the dimensions of any member of a structure where the actual service stresses are known. In the case of the impact test the results cannot be so applied. The work absorbed in breaking any given section cannot be calculated from the work absorbed in fracturing a test specimen of different dimensions. This does not, however, destroy the value of the impact test. Its comparative value is still vital in forming a judgment of the merit of a given material for certain specified purposes.

In the investigation about to be discussed, the impact test is considered solely as a means of providing a comparative measure of work done by a particular type of machine in fracturing test specimens representing certain material, and the behaviour of that material when influenced by a certain dimensional peculiarity. Information of a comparative, and not absolute, nature has been sought, but experience has shown that such comparison can be of the highest importance and of immense practical value. Modern invention has led to the design of machinery in which impact stresses are of vital importance, and, furthermore, in which impact stresses are applied to members having abrupt sectional changes. Higher fibre stresses are being utilised, and the apparent factor of safety is being reduced in many cases in order to obtain lightness of construction.

A Charpy impact testing machine of 2170 foot-pounds capacity was selected for testing the steels used in this investigation, as being particularly adapted for the rapid determination of the energy absorbed in fracturing a test specimen of comparatively large dimensions and having an abrupt change in section. The Charpy impact testing machine, in common with all other impact testing machines which have been brought forth up to the present time, has not been free from criticism, but in the author's opinion represents the best appliance available for the particular problem.

The investigation was undertaken to determine the differences in the amount of energy absorbed in fracture by dynamic stress, or the differences in resistance to impact, which are exhibited by certain representative steels when they are subjected to different temperatures.

Materials employed in the construction of ordnance are used under very different climatic conditions, temperature being a decided variable. A thorough knowledge of the effect of temperature is therefore a necessity to the designer and metallurgist in selecting material which will be satisfactory under all conditions. Other machinery not necessarily connected with ordnance work, such as aeroplanes, tractors, automobiles, and rolling-stock of all classes, is subjected to wide temperature changes which have great influence on the physical characteristics of the materials of which it is constructed.

It is evident that all machinery which is operated in the open in latitudes where there are wide ranges of temperature, such as occur in practically all the northern states, will be called upon to resist severe stresses at those temperatures, and, in the case of ordnance, automobiles, tractors, and aeroplanes, such conditions are liable to be exaggerated, since such types of machinery are frequently allowed to remain cold for long periods and then suddenly placed at work, passing quickly from the lowest atmospheric temperature to the highest working temperature. In the case of aeroplanes the machinery may operate at the highest surface atmospheric temperature, and in a very short space of time arrive at altitudes where it will be exposed to temperatures lower than any experienced at ground level. A traction engine or tractor, for instance, when cooled by standing idle at an atmospheric temperature of —40° F. (not unusual in certain cold climates), may be started and put to capacity in a very short space of time, the starting subjecting the parts to the severest shocks and impacts. It may be added that failures have occurred under such conditions. It is thus of the highest importance to manufacturers of ordnance, automobiles, tractors, and aeroplanes that reliable information be available as to the behaviour of materials when subjected to dynamic stresses at widely differing temperatures.

There are many districts where great extremes of heat and cold occur. It is recorded at one station in North Dakota that in a period of twenty-six years the maximum temperature attained was 108° F. and the minimum —52° F., or a total variation of 160° F.

The subject of the behaviour of commonly used steels under impact stresses when subjected to different temperatures has received attention from many writers. Andrews[1] and others investigated the effect of low temperatures on railroad axles and rails, Kuczera and Reinisch[2] were among the first to make impact tests on iron and steel at different temperatures, Koepcke and Hartig[3] examined the behaviour of cast iron and steel at temperatures as low as —100° C., Mehrtens[4] and Ledebur[5] and others also conducted impact and bending tests on steels at low temperatures. A. Le Chatelier[6] contributed a number of papers on the influence of temperature on the mechanical properties of metals, including resistance to impact stresses. Charpy[7] published an account of a comprehensive research on the effect of temperature on the impact resistance of certain steels, and in later years Guillet and Revillon,[8] Goerens and Hartel,[9] Reinhold,[10] Kaiser,[11] and Chevenard[12] have made investigations on similar lines.

MATERIAL INVESTIGATED.

It was deemed advisable to investigate material of a nature in common use and representative of the types of steel employed in the construction of ordnance and automotive machinery. Six steels were therefore chosen representing a high, medium, and low carbon steel, a low carbon nickel-chromium, a medium carbon nickel-chromium, and a medium carbon nickel steel. The analyses of these steels were as follows :

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[1] *Proceedings of the Institution of Civil Engineers*, 1886, 1888, 1890, and 1893.

[2] *Mitt. über Gegenstand des Artillerie und Genie Wesens*, 1892.

[3] *Der Civilingenieur*, 1892, p. 207.

[4] *Stahl und Eisen*, February 1892, p. 196.

[5] *Soc. d'encour. pour l'Industrie Nationale*, 1899, p. 1155.

[6] *Ibid.*, "Contribution à l'étude de la Fragilité dans les fers et les aciers."

[7] *Bull. de la Soc. des Ingenieurs Civils*, vol. ii. p. 562.

[8] *Revue de Métallurgie*, 1910, p. 837.

[9] *Zeitschrift für anorganische Chemie*, 1913, vol. lxxxi. p. 130.

[10] *Ferrum*, 1916, p. 97.

[11] *Stahl und Eisen*, 1921, p. 333.

[12] *Revue de Métallurgie*, April 1922, p. 209.

TABLE I.

Steel.	C. Per Cent.	Mn. Per Cent.	Si. Per Cent.	P. Per Cent.	S. Per Cent.	Ni. Per Cent.	Cr. Per Cent.
A. Average of 3 determinations .	0·209	0·42	0·206	0·016	0·030	1·94	0·99
B. Average of 4 determinations .	0·315	0·41	0·223	0·045	0·036	3·30	0·107
C. Average of 4 determinations .	0·363	0·40	0·472	0·015	0·018	1·92	0·97
D. Average of 4 determinations .	0·363	0·68	0·260	0·054	0·044	0·35	0·9
E. Average of 3 determinations .	0·833	0·65	0·123	0·027	0·029	0·24	0·04
G. Average of 3 determinations .	0·176	0·69	0·053	0·053	0·036	0·11	0·016

It will be observed that five of these steels substantially correspond with the specifications of the American Society of Automotive Engineers, Steel A corresponding with S.A.E. 3220, Steel B corresponding with S.A.E. 2335, Steel C corresponding with S.A.E. 3240, Steel D corresponding with S.A.E. 1035, and Steel G corresponding with S.A.E. 1020.

Steels A, B, and C were made in the electric furnace, and Steels D, E, and G in the acid open-hearth furnace. The material for testing was rolled bar $1\frac{3}{8}$ inch square section, and was received in lengths of 9 to 16 feet.

METHODS OF TESTING.

To ascertain the degree of uniformity of the material, $6\frac{1}{2}$ inches was cut from the ends of each bar and annealed in order to provide two specimens from each original length to be tested at normal temperature. The anneal was similar to that adopted for the temperature tests. These lengths were machined into Charpy transverse test specimens, and marked in a manner to show the grade of steel and the original bar from which they were derived.

The following table gives the significant results obtained from this series of tests :

TABLE II.—*Annealed End Bars.*

Steel.	Average. Ft.-lbs.	Mean Divergence. Ft.-lbs.	Per Cent.	Maximum above Average. Ft.-lbs.	Per Cent.	Maximum below Average. Ft.-lbs.	Per Cent.	No. of Specimens.
A	447·85	25·36	5·6	46·16	10·9	59·01	19·2	14
B	159·97	18·98	11·2	29·53	18·3	40·99	25·6	12
C	192·99	8·6	4·4	17·41	9·0	11·45	5·9	13
D	33·62	4·78	14·2	13·03	38·7	7·01	20·8	12
E	20·24	1·74	8·59	3·05	15·0	3·61	17·8	5
G	59·87	2·91	4·86	1·98	3·3	8·74	14·6	6

The divergences from the average result of test expressed in foot-pounds are averaged and shown in Table II. as the mean divergence. The mean divergence is also expressed as a percentage of the average. Both the maximum divergences above and below the average are given in foot-pounds and expressed as percentages of the average. This table will be referred to later in the discussion of the experimental results.

In this investigation tests were made on three test specimens of each composition, in both annealed and heat-treated conditions, and at each temperature. The specimens of any one steel tested at a given temperature were not adjacent in the same bar but were distributed throughout the entire amount of the material used in the test. After the end test specimens from each bar had been tested for uniformity, the remaining material was laid off into 6½-inch lengths suitable for machining into Charpy test specimens, and each 6½-inch length was marked according to a system which indicated the steel, the temperature at which tested, the heat treatment, its position in the bar, and the original bar from which it came. The method is indicated by the example of an original bar shown on p. 82.

In Fig. 1 the end bars carry the original mill markings, with the addition of a serial number. The first letter of each marked section of the remaining bars denotes the grade of steel, A thus taking the significance of 0·20 carbon. The first figure denotes the number of the test specimen, also denoting the heat treatment

TABLE III.—*Tensile Properties at Normal Temperature.*

Steels.	Steel A.	Steel B.	Steel C.	Steel D.	Steel E.	Steel G.
	C. 0·21. Mn. 0·42 Ni. 1·94. Cr. 0·99.	C. 0·31. Mn. 0·41. Ni. 3·30. Cr.	C. 0·36. Mn. 0·40. Ni. 1·92. Cr. 0·98.	C. 0·36. Mn. 0·68. Ni. Cr.	C. 0·82. Mn. 0·62. Ni. Cr.	C. 0·17. Mn. 0·69. Ni. Cr.
	Annealed. Average of Three Specimens.					
Yield point, lbs. per sq. in.	40,000	45,500	42,500	35,500	35,850	26,500
Tensile strength, lbs. per sq. in.	65,850	76,350	89,150	71,500	100,000	50,350
Elongation in 2 inches, per cent.	30·6	24·5	21·3	25·6	13	38·2
Reduction of area, per cent.	58·9	41·3	41·3	39·2	13·4	63·1
Fracture	Silky	Silky	Silky	Silky	Granular	Silky
	Heat-Treated. Average of Three Specimens.					
Yield point, lbs. per sq. in.	50,750	77,650	101,500	47,500	93,500	33,000
Tensile strength, lbs. per sq. in.	81,500	99,350	122,650	81,650	151,850	57,350
Elongation in 2 inches, per cent.	21	22·8	20·1	26	11·8	35·6
Reduction of area, per cent.	67	58·1	58·1	60·6	26·2	69·2
Fracture	Silky	Silky serrated	Silky serrated	Silky	Granular	Silky

(odd numbers indicating annealed, and even numbers quenched

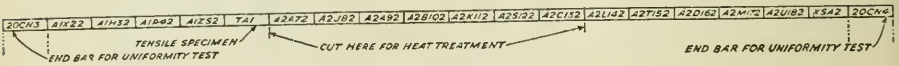

20CN3
A1X22
A1H32
A1P42
A1Z52
TA1
A2A72
A2J82
A2A92
A2B102
A2K112
A2S122
A2C132
A2L142
A2T152
A2D162
A2M172
A2U182
XSA2
20CN4
TENSILE SPECIMEN
END BAR FOR UNIFORMITY TEST
CUT HERE FOR HEAT TREATMENT
END BAR FOR UNIFORMITY TEST

FIG. 1.

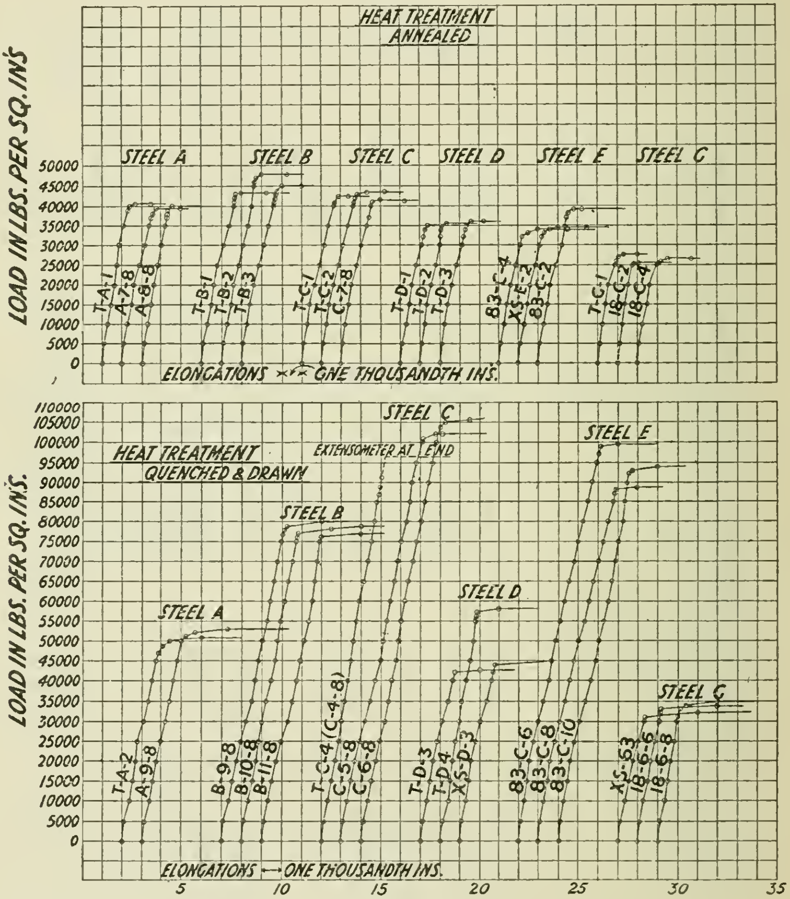


FIG. 2.—Stress-Strain Curves of Tensile Specimens.

and drawn); the second letter denotes the temperature at which the specimen was tested, the number immediately following it designates the position of the specimen in the bar, and the final figure denotes the original bar from which the specimen was cut. Thus, legend A1X22 designates Steel A, test specimen 1 in the annealed condition, tested at temperature X or 750° F., and the second test specimen cut from the original bar 2. This method provided a complete record of the specimen, enabling its history to be traced in detail from the original bar from which it was derived.

The tensile properties of the material at 75° F. were ascertained by testing six tensile specimens from each grade of steel, distributed throughout the entire lot. The location of one of these tensile specimens can be seen in Fig. 1, indicated by the letter T. Of these six tensile specimens, three were annealed and three were quenched and drawn before machining, the heat treatment given in each case being identical with the heat treatment to which the impact specimens used in the temperature impact tests were subjected. The stress-strain diagrams up to the yield point are shown in Fig. 2, and the tensile properties obtained are given in Table III.

In regard to annealing and heat treatment, the original bars were first cut into lengths suitable for the furnace, as indicated in Fig. 1, and annealed. The material for test specimens in the heat-treated condition was subsequently quenched and drawn. Thus it will be seen that the material was annealed and heat treated when in lengths of about 3 or 4 feet, except in a few cases where it was necessary to cut off single 6½-inch lengths to carry out the original scheme.

Temperatures of all heat treatments were controlled by means of base metal thermocouples, recording on Leeds and Northrup recording potentiometers. The furnaces were oil-fired.

All material, regardless of subsequent treatment, was first annealed as follows :

Steel					
A.	Heated to	1652° F.,	held 1½ hours,	and cooled	in furnace.
B.	,,	,,	,,	,,	,,
C.	,,	,,	,,	,,	,,
D.	,,	,,	,,	,,	,,
E.	,,	1553° F.,	,,	,,	,,
G.	,,	1697° F.,	,,	,,	,,

The material to be tested in the heat-treated condition was then treated as follows :

Steel

A. Heated to 1580° F., held one hour.
Quenched in oil five minutes.
Reheated to 1400° F., held one hour.
Quenched in oil five minutes.
Reheated to 500° F., held one hour.
Cooled in air.

B. Heated to 1517° F., held one hour.
Quenched in oil five minutes.
Reheated to 1112° F., held one hour.
Cooled in furnace.

C. Heated to 1517° F., held one hour.
Quenched in oil five minutes.
Reheated to 1112° F., held one hour.
Cooled in furnace.

D. Heated to 1562° F., held one hour.
Quenched in water one minute.
Reheated to 1112° F., held one hour.
Cooled in furnace.

E. Heated to 1472° F., held one hour.
Quenched in oil five minutes.
Reheated to 842° F., held one hour.
Cooled in furnace.

G. Heated to 1652° F., held one hour.
Quenched in oil five minutes.
Reheated to 1400° F., held one hour.
Quenched in oil five minutes.
Reheated to 500° F., held one hour.
Cooled in air.

The annealed and heat-treated material was then machined into Charpy test specimens.

It seems proper to discuss in a brief manner the reasons leading to the selection of the above heat treatments.

Steel A, a low carbon nickel-chromium steel commonly used for work which is to be carburised, was heated to 1580° F. and held one hour, and then quenched in oil, to approximate the carburising treatment. After this operation it was reheated to 1400° F., quenched in oil, and drawn at 500° F., in order to approximate the treatment given to a carburised part made of this material. In other words, Steel A as tested in the heat-treated condition represented the condition of the core of a case-hardened article made from a steel of a similar composition.

Steel B, representing a medium carbon nickel alloy steel, such as is generally used for parts requiring strength and toughness, was quenched in oil from 1517° F. and reheated to 1112° F.

for one hour. By this treatment the steel acquired a condition which gave a yield point of 77,650 pounds per square inch, and a tensile strength of 99,350 pounds per square inch. A relatively high tempering or draw temperature was selected for this composition in order that a reasonably high resistance to impact might be expected, and at the same time average tensile properties obtained. It should also be noted that steels of this composition are extensively used in gun construction, and the tensile properties as given in Table III. are those frequently encountered in this class of work.

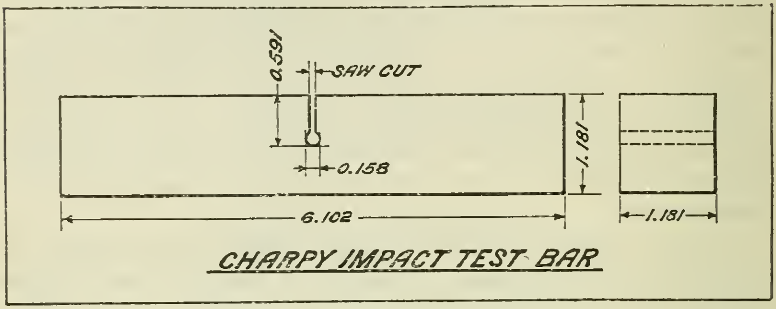
Steel C, being a medium carbon nickel-chromium alloy, is often used for heat-treated forging and machine parts, and is selected by many engineers because of its susceptibility to greater penetration of the effect produced by heat treatment than a simple nickel alloy steel. This steel received the same treatment as Steel B, and a yield point of 101,500 pounds per square inch obtained. It will be noted that both Steels B and C were subjected to a simple quench followed by a tempering or drawing operation, the steels, however, having been annealed before heat treatment.

Steel D is often used for plain carbon steel forgings, and received a simple quench and tempering treatment.

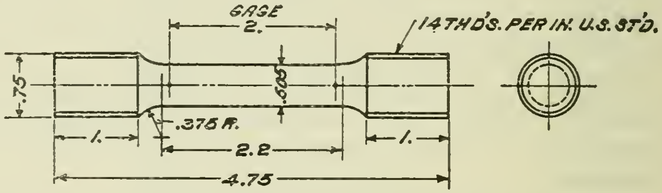
Steel E represents a plain carbon steel of a carbon content which might be encountered in certain classes of springs, as well as in tools. This steel was quenched in oil from 1472° F. and tempered at 842° F. A higher tempering or drawing temperature was selected than would be utilised for tools, in order to facilitate machining, and, moreover, certain springs of this composition are tempered at approximately this temperature.

Steel G is a simple low carbon steel which can be used for a large variety of case-hardened parts, being also employed in the manufacture of tubes and other cold-rolled and drawn shapes. A heat treatment was chosen, however, which would leave this steel in a condition similar to that of the core of a case-hardened article made from a steel of this composition.

After the heat-treatment operations the material was cut into 6½-inch lengths and machined into Charpy test specimens and tensile test specimens, as shown in Fig. 3. The Charpy test specimen had the dimensions recommended by Charpy, except that the length was reduced by 5 millimetres in order to give absolute clearance from the anvil of the testing machine. Great care was taken to cut the notch in the same relative position in each test specimen as regards the original rolled bar.



CHARPY IMPACT TEST BAR



TENSILE SPECIMEN
AREA = .2 SQ. IN.

Fig. 3.—Dimensions of Test Specimens.

Impact Testing Machine Used.

The tests were made on a Charpy pendulum machine of a capacity of 2170 foot-pounds. The weight of the pendulum was 212·45 pounds, the radius of centre of gravity 5·33 feet, and the velocity of impact was 25·77 feet per second. The foot-pounds were computed from the excess angle, and corrections were made for friction, air resistance, and projection of the broken fragments. The excess angles were read by two independent observers from a scale and estimated to ½ tenths.

The tensile test specimens were tested on the United States

Government emery testing machine at Watertown Arsenal, elongations being measured with a Berry extensometer. Brinell tests were made on an Alpha Brinell machine using a 10-millimetre ball and 3000 kilogrammes pressure; the impressions were made on the broken Charpy specimens.

METHODS OF OBTAINING THE DESIRED TEMPERATURES.

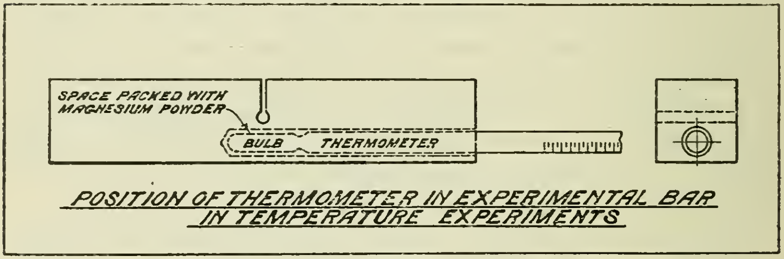
Three specimens of each steel in both the annealed and heat-treated conditions were tested at the following temperatures: — 80°, — 60°, — 40°, — 20°, 0°, 15°, 32°, 50°, 70°, 90°, 110°, 130°, 150°, 175°, 200°, 225°, 250°, 350°, 500°, 750°, and 1000° F.

Temperatures from 50° to 0° F. were obtained in the actual tests by favourable atmospheric conditions during the winter of 1921 and 1922; temperatures from — 20° to — 80° were obtained by the use of carbon dioxide snow. The specimens were immersed in a bath of acetone which was, to begin with, cooled to 0° F. by means of immersion in a freezing mixture of ice, salt, and calcium chloride. The acetone was then cooled to the lower temperatures by the direct addition of carbon dioxide snow.

Temperatures from 90° to 350° F. were obtained in a Freas constant temperature electric oven, and from 500° to 1000° F. in a Hoskins Type FB electric muffle furnace, the apparatus being placed as near to the impact testing machine as was convenient.

The temperature of the test specimens was ascertained in each case as follows: Temperatures from 0° to 350° F. were measured by the use of specially made mercury thermometers. From — 80° to 0° F. specially made alcohol thermometers were used. A hole was drilled longitudinally in a dummy specimen to allow of the insertion of a thermometer, the hole being of such a depth that the bulb of the thermometer was located opposite the notch (see Fig. 4). The intervening space between the material of the dummy specimen and the bulb of the thermometer was closely packed with powdered metallic magnesium, thus avoiding air spaces between the specimen and the thermometer. Magnesium powder was chosen for this purpose because its specific heat closely approximates that of steel. In actual testing the dummy specimen was placed in the bath or oven together with the actual test specimens. Oven and bath temperatures were determined directly. When the dummy specimen had reached the desired temperature and this temperature had remained constant for a considerable period, a test specimen was withdrawn and tested. Since previous experiments with several dummy specimens in both bath and oven indicated great uniformity, it is believed that the actual temperatures of the test specimens closely approximated that of the dummy.

Temperatures from 500° to 1000° F. were ascertained by means of a standard platinum-rhodium thermocouple inserted in the centre of the notch of the actual test specimen (no dummy being used in this temperature range) and packed with asbestos wool, thus bringing the hot junction of the thermocouple into contact with the steel of the test specimen at the bottom of the notch. Millivolts were read on a Leeds and Northrup precision potentiometer. The temperature of the muffle furnace was also recorded by a base metal couple and read directly in degrees Fahrenheit on a Leeds and Northrup recording potentiometer.



POSITION OF THERMOMETER IN EXPERIMENTAL BAR IN TEMPERATURE EXPERIMENTS

Fig. 4.

The change of temperature which the test specimens underwent during the time interval between the moment of removal from the heating or cooling media to the moment of impact in the actual tests was determined by an exhaustive series of experiments. A dummy test specimen with thermometer inserted, as previously described, was heated or cooled to the various temperatures adopted in the tests. The specimen was then transferred to the anvil of the testing machine and the change of temperature recorded per second of time. From a large number of experiments made at each temperature, cooling or heating curves were obtained from which a close approximation of the loss or gain of heat of the test specimen per second was available. Typical curves are shown in Fig. 5.

During the actual tests the time in transference of the test specimen from the heating or cooling media was determined by means of a stop-watch, and thus the actual temperature at the moment of impact ascertained. The following table shows

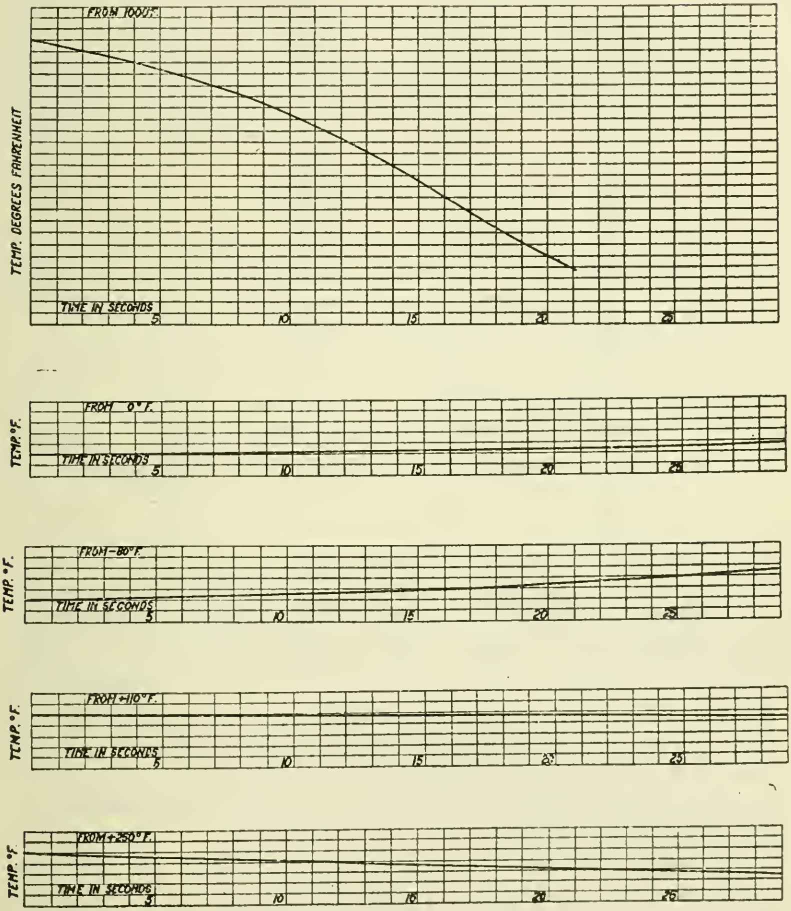


Fig. 5.—Temperature Curves showing Change of Temperature of Specimens as a Function of Time.

the average time in seconds during transference for the tests at the various temperatures :

TABLE IV.

Temperature of Test. ° F.	Average Time in Seconds to Impact.	Loss of Heat. ° F.	Gain of Heat. ° F.
1000	15·0	12·5	...
750	14·9	7·3	...
500	13·1	4·25	...
350	12·1	1·15	...
250	11·1	1·00	...
225	10·3	0·75	...
200	10·1	0·5	...
175	10·0	0·25	...
150	9·9	0·15	...
125	10·4	0·2	...
110	11·0	0·15	...
90	11·7	0·15	...
70	...	...	...
50	24·2	...	0·15
32	22·5	...	0·15
15	16·5	...	0·2
0	11·1	...	0·15
— 20	8·7	...	0·15
— 40	8·7	...	0·4
— 60	8·6	...	0·4
— 80	8·2	...	0·5

An examination of Table IV. shows that the change in temperature due to the loss or gain of heat by the specimen during transfer from the heating or cooling media to the testing machine is in general quite small, and is not sufficient to cause the results of tests at the nominal temperatures to be questioned. In the case of the three highest test temperatures, however, the loss of heat is noticeable, but it is considered that the general conclusions are not affected thereby.

DIMENSIONS OF TEST SPECIMENS.

Each test specimen was carefully measured before test, and the area of cross-section at the notch computed from the average of three measurements taken at each end and centre of notch.

The average area of cross-section at notch of the 733 test specimens taken was 0·6889 square inch.

The mean divergence from this average was 0·0031 square inch, or 0·45 per cent. of the average.

The maximum divergence above the average area was 0·0181 square inch, or 2·62 per cent., and the maximum divergence below the average area was 0·0159 square inch, or 2·30 per cent. It was considered that divergences from the average of this order of magnitude were not sufficient to affect results materially, and therefore results of tests have been accepted as fairly comparable as regards ruptured area.

Experimental Results.

The results obtained in this investigation are tabulated in Tables V. and VI. for the six steels examined in both the annealed and heat-treated conditions.

A graph has been drawn for each steel in both the annealed and heat-treated conditions, the foot-pounds absorbed by rupture being represented as ordinates and the temperatures of test as abscissas. The individual results of tests are shown by circles, and the mean of all tests at any temperature is given by the heavy dots.

All of the above data have been summarised on two additional graphs, the average values of test only being considered, one graph for the steel in the annealed condition and the other for the steel in the heat-treated condition. A different legend has been used in constructing each curve for convenience of comparison.

Discussion of Results.

Referring to Figs. 6 and 7, it will be observed that Steel A, in the zone of temperatures from − 80° to 0° F., had much more resistance to impact in the heat-treated condition than in the annealed condition. In the range of temperature from 0° to 100° F. the steel in the heat-treated condition also had a greater resistance to impact than the same material in the annealed condition. In the range from 100° to 200° F. there was very little difference. Above 200° F. the steel in the annealed condition gave a higher energy absorption for rupture in the annealed condition than in the heat-treated condition, with the exception of the tests at 1000° F., where the heat-treated condition was again superior to the annealed condition.

For purposes of comparison certain specific figures will now be given. At a temperature of – 60° F., Steel A in the heat-treated condition had almost twice the resistance to impact as had the same steel in the annealed condition. The steel in the annealed condition rapidly increased its resistance to impact until at a temperature of 0° F. Steel A in the annealed condition gave an average result of 324 foot-pounds as compared with 466 foot-pounds for the heat-treated condition. Above 0° F. the impact resistance in the heat-treated condition also improved, so that at 110° F. the average result obtained upon Steel A in

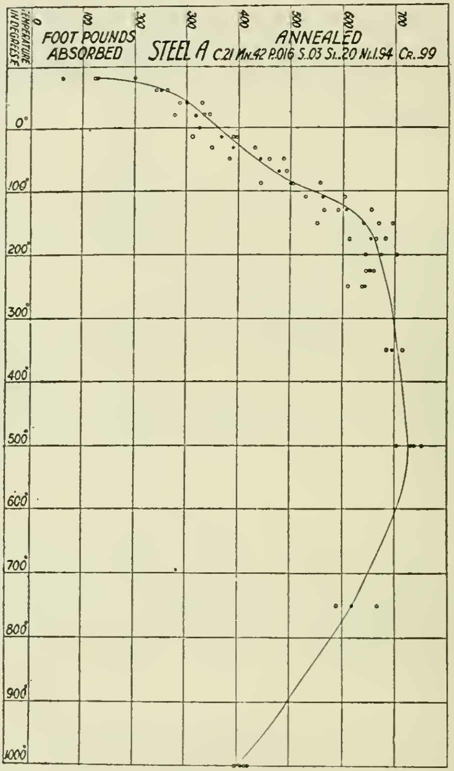


FIG. 6.

the annealed condition was 560 foot-pounds as compared with 649 foot-pounds in the heat-treated condition.

In similar manner a great many other comparisons can be made from the two curves, but it is of particular interest to note the great superiority of this steel in the heat-treated condition as compared with the annealed condition in the very low temperature range.

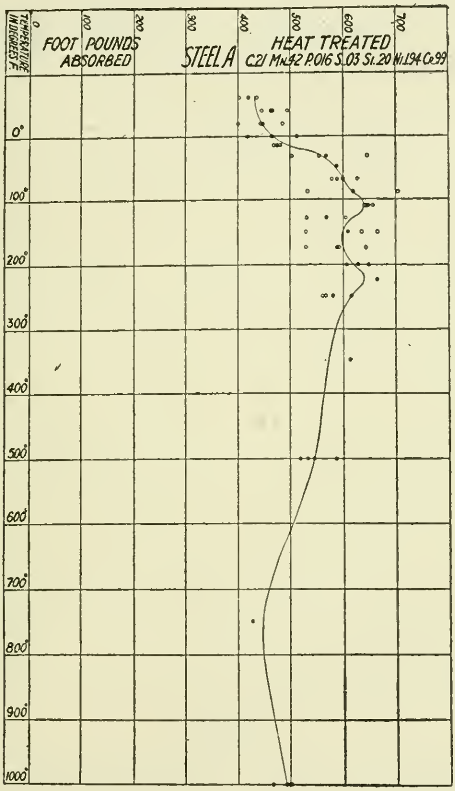


Fig. 7.

It may be interesting at this point to refer to the structure of Steel A in the annealed and heat-treated conditions. Plate II. (Nos. 1 and 2 respectively) illustrates the structure of the steel in the annealed condition, and after heat treatment. Both of the above photomicrographs referred to show the structure at 100 diameters. It is, of course, obvious that the ferrite is very much more finely divided when in the heat-treated condition than when in the annealed condition.

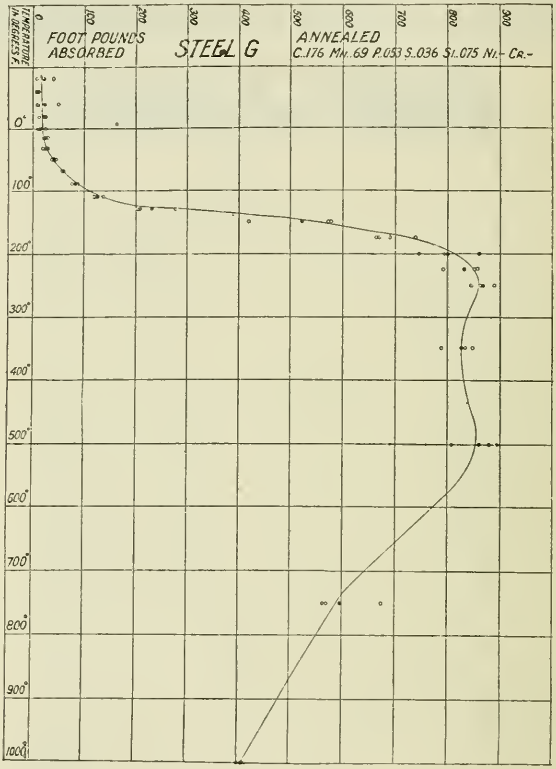


FIG. 8.

The next discussion will deal with Steel G—a steel utilised in many cases for similar purposes as Steel A, namely, for case-hardened parts, its behaviour being illustrated in Figs. 8 and 9. The essential difference between the two steels lies in the composition, Steel G being a simple carbon steel, whereas Steel A is a nickel-chromium alloy, also containing some 0·04 per cent. more carbon than Steel G.

Comparing Steel G in the annealed and heat-treated conditions in the low temperature range, it will be observed that in the annealed condition no appreciable increase in the resistance to impact is apparent until a temperature of 32° F. is reached. In fact, no decided sharp break in the curve occurs below 90° F.

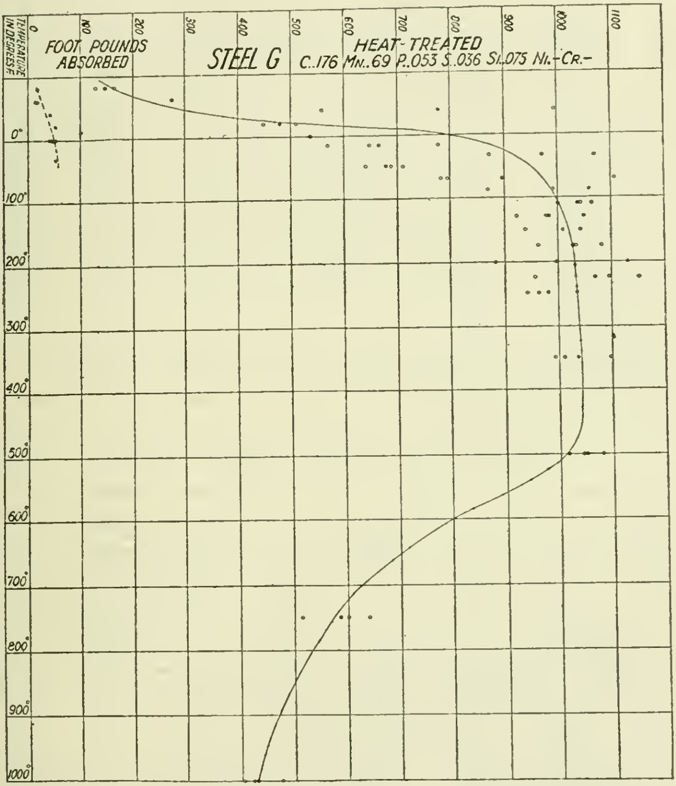


Fig. 9.

The results obtained upon this steel in the heat-treated condition, however, were very erratic. In some of the temperature tests below 32° F., individual values were obtained varying from approximately 50 to 1000 foot-pounds. The lower values appeared to fall on a separate curve, which has been plotted in the form of a broken line, but the average of the other tests gave a curve similar to that obtained from the steel in the annealed condition, with the exception that the sharp increase in resistance to impact occurred at a much lower temperature, namely, between — 80° and 0° F., whereas in the annealed condition the same sharp increase occurred between the temperatures 100° to 200° F.

Referring again to Steel G in the annealed condition, attention is invited to the slope of the curve in the vicinity of 70° F., which is the temperature at which practically all routine tests are conducted. The temperature in the laboratory at Watertown Arsenal normally varies from 65° to 80° F., with 70° F. as the approximate average temperature. For the particular steel under discussion, in the annealed condition, a test conducted at 80° F. would give a result approximately 15 per cent. higher than a similar test on the same material at 70° F. In view of the possible rapid change of impact value in the zone of normal temperature, it is very vital that all such tests be conducted at a standard temperature.

Again referring to Steel A in the annealed condition in the temperature range below 100° F. or the normal working range, it is to be noted that much superior values were obtained than in the case of Steel G in a like condition. The average foot-pounds absorbed by Steel G in the annealed condition below a temperature of 0° F. was approximately 25 foot-pounds, whereas for Steel A in the same condition it was approximately 250 foot-pounds. On the other hand, Steel G in the heat-treated condition gave some values much superior to any obtained upon Steel A in the same condition. It is to be noted, however, that in the low temperature range, namely, from — 80° to 0° F., Steel A was again superior to Steel G.

Plate III. shows the structure of Steel G in the annealed and heat-treated conditions. It would appear that the breaking up of the ferrite by heat treatment had a marked effect in moving to the left that portion of the curve where the resistance to impact was rapidly increasing. Stated in other words, the breaking up of the ferrite by heat treatment had decidedly increased the resistance to impact in the lower temperature range.

Figs. 10 and 11 represent the curves derived from Steel B, a medium carbon nickel alloy steel. This steel is extensively used in the manufacture of ordnance, and since a great many major and minor calibre guns have been made from a composi-

s Absorbed in Fracture at Various Temperatures.)

Steel E.				Steel G.			
C. 0·82.	Mn. 0·62.	Ni. —	Cr. —	C. 0·17.	Mn. 0·69.	Ni. —	Cr. —
E–1.	E–3.	E–5.	Average.	G–1.	G–3.	G–5.	Average.
16·63	30·01	16·63	21·09	19·53	42·34	10·92	24·26
15·69	31·10	30·01	25·60	11·64	13·74	11·64	12·34
16·63	17·07	26·25	19·98	11·14	53·23	11·93	25·43
32·98	32·98	15·76	27·24	27·19	14·75	26·25	22·71
18·58	40·86	21·33	26·92	17·50	11·93	26·03	18·48
20·25	22·40	26·54	23·06	23·14	30·01	26·03	26·39
15·91	31·82	15·18	20·97	29·63	21·12	31·10	27·28
21·33	18·51	17·57	19·14	40·86	40·86	46·00	42·57
28·20	26·76	16·62	23·86	61·84	61·84	60·75	61·48
20·61	31·96	...	31·29	88·24	78·11	88·24	84·86
43·39	27·57	45·92	38·96	122·60	137·42	121·14	127·05
57·50	43·39	22·78	41·22	207·58	210·48	280·64	232·90
54·24	44·98	52·07	50·43	572·13	577·91	420·96	523·66
58·94	61·84	92·72	71·16	665·29	739·56	670·49	691·78
62·05	93·08	123·68	92·93	747·16	794·99	862·17	801·44
67·62	83·61	71·96	74·39	793·09	857·47	852·48	834·34
96·19	69·14	92·20	85·84	846·98	866·15	891·24	868·12
126·21	127·37	115·36	122·98	846·83	850·44	789·12	828·79
164·18	178·65	184·15	175·66	808·79	894·14	880·25	861·06
190·95	173·95	176·84	180·58	560·55	666·88	567·79	598·40
142·70	141·40	150·08	144·72	414·45	420·96	400·56	411·99
Heat 1553° for 1½ hours. Cool in furnace.				Heat 1697° for 1½ hours. Cool in furnace.			

unds Absorbed in Fracture at Various Temperatures.)

Steel E.				Steel G.			
C. 0·82.	Mn. 0·62.	Ni. —	Cr. —	C. 0·17.	Mn. 0·69.	Ni. —	Cr. —
E–2.	E–4.	E–6.	Average.	G–2.	G–4.	G–6.	Average.
43·03	115·36	35·08	64·49	164·18	18·51	128·74	103·81
31·82	44·84	34·92	37·19	15·70	17·35	*273·04*	16·52–273·04
64·95	...	31·96	48·45	994·82	556·65	*42·96*	42·96–775·73
45·92	98·65	27·70	57·43	507·97	*52·22*	446·63	52·22–477·30
28·57	28·93	42·96	33·48	52·07	*534·15*	41·95	47·01–534·15
41·95	31·10	27·12	33·39	567·79	646·26	775·37	663·14
57·49	80·43	46·07	61·33	*52·22*	1066·28	870·00	52·22–968·14
...	84·26	...	84·26	638·67	686·05	708·47	677·73
43·98	87·08	...	65·53	1105·58	793·09	780·44	893·02
84·26	60·75	87·15	77·38	1312·21	990·56	867·23	1056·66
74·10	94·75	98·73	89·19	1041·04	1000·68	1061·08	1034·26
82·45	69·79	95·11	82·45	1048·42	976·45	920·40	981·75
80·86	83·17	76·88	80·30	936·52	1040·99	1040·99	1006·16
...	108·49	139·45	123·97	1030·97	1081·55	960·54	1024·35
241·94	148·27	138·87	176·36	1127·90	971·75	880·25	993·30
142·70	157·31	207·58	169·53	1151·85	954·39	1094·35	1066·86
379·73	177·35	148·99	235·36	1031·85	960·54	940·65	977·68
173·95	157·67	177·35	169·65	990·55	1010·45	1096·16	1032·38
210·48	221·69	255·32	229·16	1041·19	1020·72	1077·56	1046·39
223·13	174·82	181·54	193·16	599·47	515·13	636·86	583·82
156·52	164·18	159·12	159·94	424·28	403·96	472·67	433·63
Heat 1472° for 1 hour. Quench oil 5 mins. „ 842° „ 1 „ Cool in furnace.				Heat 1652° for 1 hour. Quench oil 5 mins. „ 1400° „ 1 „ „ 5 „ „ 500° „ 1 „ Cool in air.			

F. C. Langenberg's Paper.

To face p. 96.

TABLE V.—CHARPY RESULTS FROM TESTS MADE ON MATERIAL IN ANNEALED CONDITION. (Foot-Pounds Absorbed in Fracture at Various Temperatures.)

Temperature of Test. Deg. Fahr.	Steel A.				Steel B.				Steel C.				Steel D.				Steel E.				Steel G.			
	C. 0·21.	Mn. 0·42.	Ni. 1·94.	Cr. 0·99.	C. 0·31.	Mn. 0·41.	Ni. 3·30.	Cr. —	C. 0·36.	Mn. 0·40.	Ni. 1·92.	Cr. 0·98.	C. 0·36.	Mn. 0·68.	Ni. —	Cr. —	C. 0·82.	Mn. 0·62.	Ni. —	Cr. —	C. 0·17.	Mn. 0·69.	Ni. —	Cr. —
	A–1.	A–3.	A–5.	Average.	B–1.	B–3.	B–5.	Average.	C–1.	C–3.	C–5.	Average.	D–1.	D–3.	D–5.	Average.	E–1.	E–3.	E–5.	Average.	G–1.	G–3.	G–5.	Average.
−80° A	122·59	60·75	199·12	127·48	19·53	10·92	20·47	16·97	26·04	...	28·21	27·23	29·65	13·38	12·87	18·63	16·63	30·01	16·63	21·09	19·53	42·34	10·92	24·26
−60° B	249·2	259·45	238·69	249·1	17·35	18·51	13·38	16·41	25·31	31·10	56·42	37·61	15·69	13·02	26·04	18·25	15·69	31·10	30·01	25·60	11·64	13·74	11·64	12·34
−40° C	316·08	297·50	283·82	299·13	19·52	18·51	21·41	19·81	58·58	16·63	16·63	30·61	16·63	17·07	12·58	15·42	16·63	17·07	26·25	19·98	11·14	53·23	11·93	25·43
−20° D	341·39	330·25	274·56	315·40	21·4	40·93	...	31·17	83·61	41·95	35·94	53·83	35·94	11·93	15·76	21·21	32·98	32·98	15·76	27·24	27·19	14·75	26·25	22·71
0° E	325·48	325·48	320·78	323·91	33·99	...	72·47	53·23	78·11	68·06	...	73·11	13·74	11·93	13·74	13·13	18·58	40·86	21·33	26·92	17·50	11·93	26·03	18·48
15° G	397·09	390·22	308·12	365·14	84·62	...	80·28	82·45	75·22	117·17	97·94	96·78	15·91	16·63	23·14	18·56	20·25	22·40	26·54	23·06	23·14	30·01	26·03	26·39
32° H	395·64	424·57	346·17	388·79	101·98	65·82	89·32	85·71	131·13	152·61	70·37	118·03	23·50	11·93	13·74	16·39	15·91	31·82	15·18	20·97	29·63	21·12	31·10	27·28
50° J	487·58	453·50	380·45	440·51	150·08	156·52	103·21	136·60	134·53	185·52	196·73	172·26	31·97	27·12	28·06	29·05	21·33	18·51	17·57	19·14	40·86	40·86	46·00	42·57
70° K	468·43	469·42	488·58	475·47	157·67	156·59	162·74	159·00	189·50	193·84	211·70	198·35	27·02	37·97	28·57	31·19	28·20	26·76	16·62	23·86	61·84	61·84	60·75	61·48
90° L	552·96	501·97	439·76	498·23	184·07	176·12	159·84	173·34	211·92	204·69	184·15	200·25	56·05	41·58	31·96	43·2	20·61	31·96	...	31·29	88·24	78·11	88·24	84·86
110° M	602·14	552·96	524·39	559·83	196·73	...	157·67	177·20	205·92	209·03	218·79	211·25	32·91	46·65	...	39·78	43·39	27·57	45·92	38·96	122·60	137·42	121·14	127·05
130° N	655·45	590·93	560·28	602·22	184·82	147·19	169·61	167·21	225·88	233·62	217·35	225·62	210·48	86·43	204·69	167·20	57·50	43·39	22·78	41·22	207·58	210·48	250·64	232·90
150° O	695·81	668·69	547·53	637·34	189·50	159·80	195·29	181·53	214·09	247·73	207·58	223·13	197·67	189·50	176·12	187·76	54·24	44·98	52·07	50·43	572·13	577·91	420·96	523·66
175° P	660·37	680·26	608·43	649·68	231·09	180·82	211·63	207·84	246·28	273·76	250·69	256·91	220·24	248·45	220·24	229·64	58·94	61·84	92·72	71·16	665·29	739·56	670·49	691·78
200° R	702·54	666·88	639·75	669·72	244·11	256·62	241·94	247·55	279·70	287·51	276·66	281·29	318·61	293·65	266·89	293·05	62·05	93·08	123·68	92·93	747·16	794·99	862·17	801·44
225° S	655·67	640·48	646·34	647·49	276·66	275·21	296·55	282·80	305·23	296·55	320·78	307·52	331·33	314·34	285·05	310·24	67·62	83·61	71·96	74·39	793·09	857·47	852·48	834·34
250° T	672·52	632·16	610·24	638·3	312·82	346·09	269·79	309·56	378·86	367·43	358·39	368·22	352·60	319·33	344·65	338·86	96·19	69·14	92·20	85·84	846·98	866·15	891·24	868·12
350° U	687·85	716·06	681·05	694·98	415·24	446·63	454·30	438·72	434·70	441·28	455·10	443·69	399·69	379·00	424·00	400·89	126·21	127·37	115·36	122·98	846·83	850·44	789·12	828·79
500° W	742·24	730·53	703·77	725·51	463·99	437·70	504·57	468·75	443·02	446·63	470·86	453·5	400·70	384·07	378·86	387·87	164·18	178·65	184·15	175·66	808·79	894·14	880·25	861·06
750° X	661·35	624·57	582·00	622·64	398·97	402·15	319·33	373·4	445·50	516·00	472·60	478·0	330·25	324·03	285·34	313·20	190·95	173·95	176·84	180·58	560·55	666·88	567·79	598·40
1000° Z	389·13	424·21	417·56	410·3	223·13	203·46	223·86	216·81	294·52	303·56	270·15	289·41	201·94	190·95	192·39	195·09	142·70	141·40	150·08	144·72	414·45	420·96	400·56	411·99
Anneal.	Heat 1652° for 1½ hours. Cool in furnace.				Heat 1652° for 1½ hours. Cool in furnace.				Heat 1652° for 1½ hours. Cool in furnace.				Heat 1652° for 1½ hours. Cool in furnace.				Heat 1553° for 1½ hours. Cool in furnace.				Heat 1697° for 1½ hours. Cool in furnace.			

TABLE VI.—CHARPY RESULTS FROM TESTS MADE ON MATERIAL IN HEAT-TREATED CONDITION. (Foot-Pounds Absorbed in Fracture at Various Temperatures.)

Temperature of Test. Deg. Fahr.	Steel A.				Steel B.				Steel C.				Steel D.				Steel E.				Steel G.			
	C. 0·21.	Mn. 0·42.	Ni. 1·94.	Cr. 0·99.	C. 0·31.	Mn. 0·41.	Ni. 3·30.	Cr. —	C. 0·36.	Mn. 0·40.	Ni. 1·92.	Cr. 0·98.	C. 0·36.	Mn. 0·68.	Ni. —	Cr. —	C. 0·82.	Mn. 0·63.	Ni. —	Cr. —	C. 0·17.	Mn. 0·69.	Ni. —	Cr. —
	A–2.	A–4.	A–6.	Average.	B–2.	B–4.	B–6.	Average.	C–2.	C–4.	C–6.	Average.	D–2.	D–4.	D–6.	Average.	E–2.	E–4.	E–6.	Average.	G–2.	G–4.	G–6.	Average.
−80° A	...	...	...	...	...	156·37	101·98	129·17	251·56	291·12	150·08	230·92	173·59	106·74	87·15	122·49	43·03	115·36	35·08	64·49	164·18	18·51	128·74	103·81
−60° B	437·96	403·74	...	420·85	210·48	153·84	200·71	188·34	230·38	264·00	252·43	248·93	162·74	86·43	61·84	103·67	31·82	44·84	34·92	37·19	15·70	17·35	*273·04*	16·52–273·04
−40° C	464·00	494·01	446·49	468·16	262·34	249·17	182·77	231·42	276·80	190·95	253·51	240·42	128·09	156·52	261·11	181·90	64·95	...	31·96	48·45	994·82	556·65	*42·96*	42·96–775·73
−20° D	444·97	412·28	486·85	448·03	317·74	268·41	300·53	295·56	231·81	259·52	271·52	254·28	309·78	298·91	379·51	329·40	45·92	98·65	27·70	57·43	507·97	*52·22*	446·63	52·22–477·30
0° E	1027·08	419·29	513·54	466·41	286·78	241·94	228·78	252·50	226·03	223·13	236·28	228·48	347·90	322·44	363·89	344·74	28·57	28·93	42·96	33·48	52·07	*534·15*	41·95	47·01–534·15
15° G	470·86	342·84	481·35	431·68	223·13	244·83	249·24	239·06	271·30	233·04	237·60	247·31	...	333·44	351·16	342·30	41·95	31·10	27·12	33·39	567·79	646·26	775·37	663·14
32° H	646·41	503·77	556·71	568·98	294·58	250·84	268·34	271·25	294·57	256·04	243·02	264·54	372·00	361·65	...	366·82	57·49	80·43	46·07	61·33	*52·22*	1066·28	870·00	52·22–968·14
50° J	786·22	590·21	...	688·21	299·01	184·80	224·58	236·13	255·18	299·01	267·11	273·76	439·04	527·64	300·53	422·40	...	84·26	...	84·26	638·67	686·05	708·47	677·73
70° K	629·27	590·21	580·80	600·09	330·18	296·55	...	313·36	328·73	306·68	287·15	307·52	...	...	...	...	43·98	87·08	...	65·53	1105·58	793·09	780·44	893·02
90° L	1102·30	534·85	707·38	621·10	346·02	300·38	314·54	320·31	360·63	379·00	328·73	356·13	436·15	373·07	545·94	451·72	84·26	60·75	87·15	77·38	1312·21	990·56	867·23	1056·66
110° M	646·34	657·47	642·29	648·70	346·46	335·24	363·45	348·38	350·44	394·92	388·99	378·11	379·73	...	567·79	473·76	74·10	94·75	98·73	89·19	1041·04	1000·68	1061·08	1034·26
130° N	683·96	534·88	606·84	608·56	434·70	439·04	419·15	430·96	395·64	352·10	416·62	388·12	607·57	621·67	495·46	574·90	82·45	69·79	95·11	82·45	1048·42	976·45	920·40	981·75
150° O	636·72	531·26	666·88	611·62	449·89	415·75	419·15	428·26	458·57	395·64	446·63	433·61	866·22	...	842·49	854·35	80·86	83·17	76·88	80·30	936·52	1040·99	1040·99	1006·16
175° P	593·83	531·91	644·46	590·06	465·80	474·48	492·73	477·68	458·57	450·97	442·29	450·61	886·18	785·21	925·46	865·61	...	108·49	139·45	123·97	1030·97	1081·55	960·54	1024·35
200° R	607·57	649·83	...	628·70	534·15	475·48	433·61	481·08	561·64	543·19	...	552·41	661·45	944·63	626·37	744·15	241·94	148·27	138·87	176·36	1127·90	971·75	880·25	993·30
225° S	665·29	986·58	755·84	802·57	528·73	478·10	489·52	498·78	573·43	624·56	505·44	567·81	568·87	639·75	589·20	599·27	142·70	157·31	207·58	169·53	1151·85	954·39	1094·35	1066·86
250° T	562·36	569·59	615·16	582·37	509·78	536·68	429·35	491·93	601·06	608·29	585·51	598·28	666·15	678·35	755·84	700·11	379·73	177·35	148·99	235·36	1031·85	960·54	940·65	977·68
350° U	615·96	713·89	1075·18	801·64	520·41	520·41	540·30	527·04	525·83	650·97	642·43	606·41	592·82	714·98	694·73	667·84	173·95	157·67	177·35	169·65	990·55	1010·45	1096·16	1032·38
500° W	520·77	534·95	590·21	548·62	595·63	660·37	555·85	603·95	627·46	713·17	648·80	663·12	884·23	755·84	960·61	866·87	210·48	221·69	255·32	229·16	1041·19	1020·72	1077·56	1046·39
750° X	429·64	644·46	699·43	591·18	341·39	483·16	534·88	453·14	655·44	476·07	538·71	556·74	588·18	450·25	479·69	506·04	223·13	174·82	181·54	193·16	599·47	515·13	636·86	583·82
1000° Z	467·39	499·07	503·77	490·04	325·48	325·48	282·08	311·01	379·00	384·07	424·28	395·78	263·28	272·32	307·40	281·00	156·52	164·18	159·12	159·94	424·28	403·96	472·67	433·63
Heat Treatment.	Heat 1580° for 1 hour. Quench oil 5 mins. „ 1400° „ 1 „ „ 5 „ „ 500° „ 1 „ Cool in air.				Heat 1517° for 1 hour. Quench oil 5 mins. „ 1112° „ 1 „ Cool in furnace.				Heat 1517° for 1 hour. Quench oil 5 mins. „ 1112° „ 1 „ Cool in furnace.				Heat 1562° for 1 hour. Quench water 1 min. „ 1112° „ 1 „ Cool in furnace.				Heat 1472° for 1 hour. Quench oil 5 mins. „ 842° „ 1 „ Cool in furnace.				Heat 1652° for 1 hour. Quench oil 5 mins. „ 1400° „ 1 „ „ 5 „ „ 500° „ 1 „ Cool in air.			

tion not dissimilar, the results are of particular interest. Below a temperature of 0° F. this material in the annealed condition had a very low impact resistance, and in fact would be classed as a brittle material. The same material in the heat-treated condition in the same temperature zone had a decidedly superior resistance to impact.

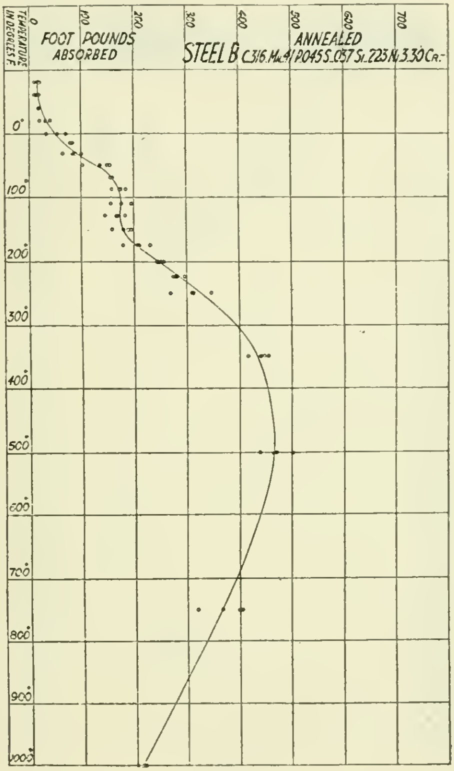


Fig. 10.

Three temperatures are selected for the purpose of comparison. At −80° F. the steel gave an average resistance to impact of 17 foot-pounds, whereas in the heat-treated condition it gave 129 foot-pounds. At a temperature of 0° F. the steel gave a resistance to impact of 53 foot-pounds in the annealed condition, although in the heat-treated condition the value was 252 foot-pounds. At 110° F. the resistance to impact in the annealed condition was 177 foot-pounds, while in the heat-treated condition it was 348 foot-pounds.

Again, it is to be observed that heat treatment served to move the curve to the left on the diagram, eliminating in the heat-treated condition the very low values of resistance to impact which occurred with the steel in the annealed condition. The structure of this steel in both the conditions in which it was tested can be clearly seen in Plate IV.

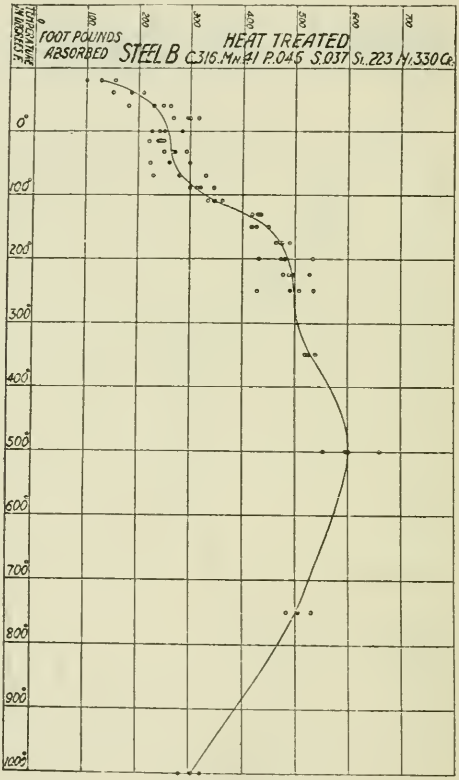


Fig. 11.

The contours of curves in Figs. 12 and 13 derived from Steel C, a medium carbon nickel-chromium alloy, are strikingly similar to those of Steel B, a plain nickel alloy. In the annealed condition the resistance to impact in the temperature range from —80° to 0° F. was very much lower than that exhibited by the same material in the heat-treated condition. Comparisons made at the same temperatures as used in discussing Steel B are presented.

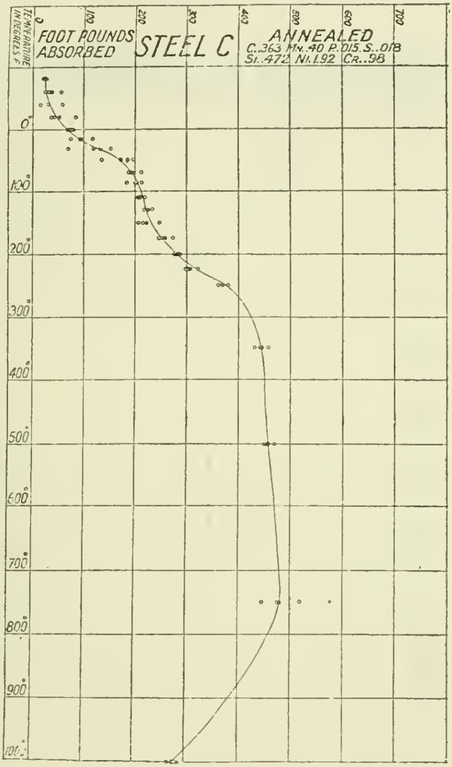


FIG. 12.

At —80° F. the resistance to impact in the annealed condition was 27 foot-pounds, whereas in the heat-treated condition it was 231 foot-pounds. At a temperature of 0° F., resistance to impact in the annealed condition was approximately 38 foot-pounds, and in the heat-treated condition it was approximately 228 foot-pounds. At a temperature of 110° F., resistance to impact in the annealed condition was 211 foot-pounds, while in the heat-treated condition it was 378 foot-pounds. Comparing for a moment Steel C with Steel B in the heat-treated condition, it is to be observed that at a temperature of −80° F. the nickel-chromium alloy, Steel C, was superior to the simple nickel alloy.

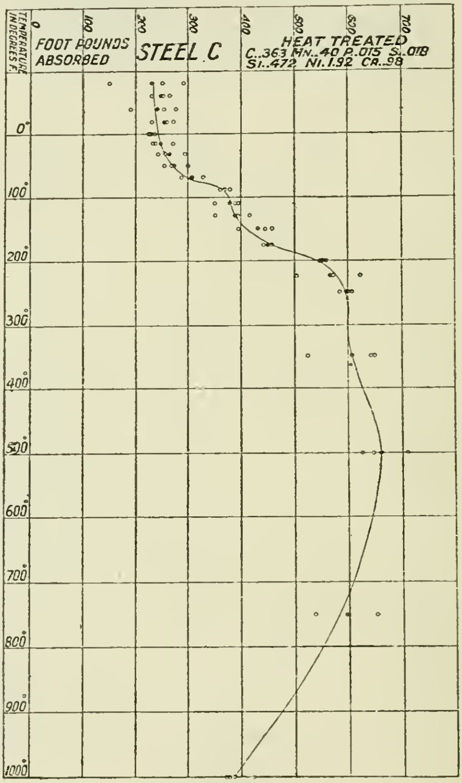


FIG. 13.

In a comparison previously referred to, Steel A, also a nickel-chromium alloy, at a temperature of −80° F., gave superior results to a simple carbon steel at this temperature. Although it may be a coincidence, it is here evident that in the two steels referred to containing chromium, the curve does not fall off rapidly between −40° and −80° F., but is apparently flat when the materials are in the heat-treated condition.

In Plate V. is depicted the structure of this material in the annealed and heat-treated conditions. The ferrite has been decidedly broken up and disseminated by the heat treatment.

Steel D, which is a simple carbon steel of medium carbon content, can be compared in its two conditions by a consideration

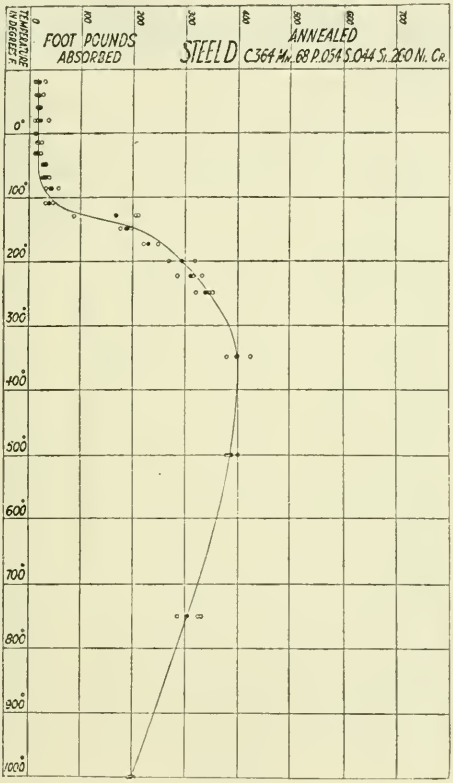


FIG. 14.

of Figs. 14 and 15. This material in the annealed condition was exceedingly brittle throughout the entire range from −80° to 100° F., increase in resistance to impact not occurring until the temperature range 100° to 200° F. was reached. This behaviour is not at all dissimilar to that of Steel G, also a simple carbon steel, but of a much lower carbon content.

At a temperature of −80° F. Steel D in the annealed condition gave a resistance to impact of approximately 17 foot-pounds, whereas in the heat-treated condition it gave a value of 122 foot-pounds. At 0° F. the average resistance to impact was 13 foot-pounds in the annealed condition, and in the heat-treated condition it was 344 foot-pounds. At a temperature of 100° F. the resistance to impact was approximately 40 foot-pounds in the annealed condition ; in the heat-treated condition, on the other hand, it was 474 foot-pounds.

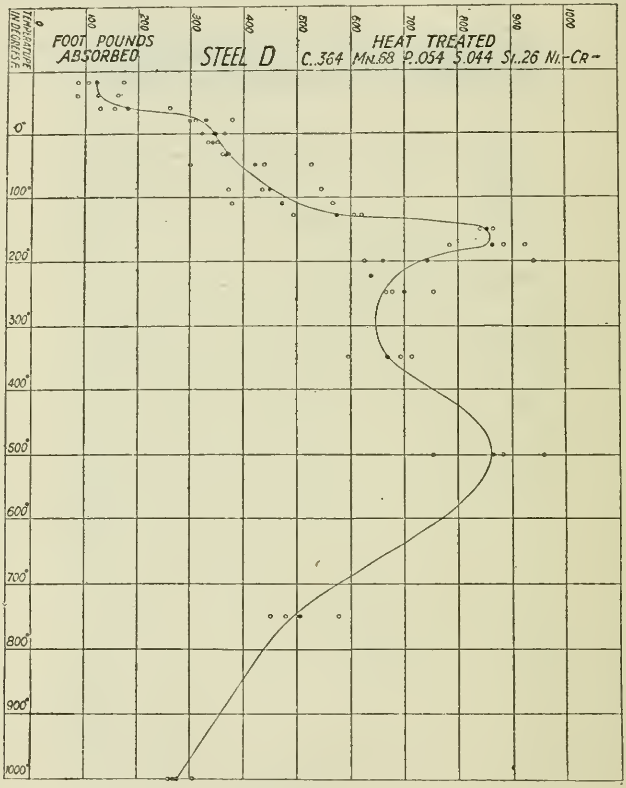


FIG. 15.

Considering for a moment Steels B, C, and D, all of which are medium carbon steels, B containing nickel, C containing nickel and chromium, and D being a simple carbon steel, it is to be observed that both the alloy steels in the annealed condition showed a decided increase in resistance to impact in the temperature range from 0° to 100° F., and at the same time the simple carbon steel showed practically no increase in this zone.

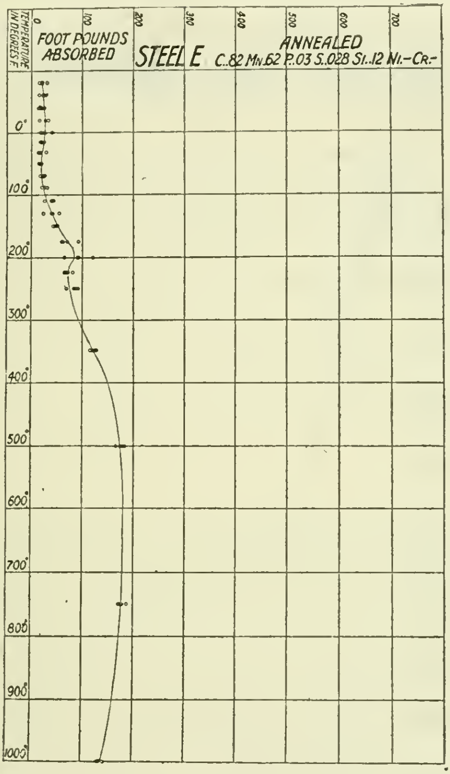


Fig. 16.

Plate VI. shows the structure of this steel in both the annealed and heat-treated conditions.

Attention may now be given to Steel E, a steel containing 0·82 per cent. carbon, and a study of Figs. 16 and 17 made. Practically no increase in resistance to impact can be observed when the steel was in the annealed condition until a temperature of 100° F. was reached. When the steel was in the heat-treated condition an increase in resistance to impact is noticeable in the temperature range from 0° F. to 100° F.

Plate VII. shows photomicrographs of the structure of this steel in the annealed and heat-treated conditions. The heat treatment has refined the structure to an appreciable degree. Although a steel of this carbon content is normally expected to give an inferior resistance to impact than steels of a lower carbon content, attention is directed to the steel in the annealed condition, where practically no improvement in impact value was observed until a temperature of 100° F. was reached. When the steel was in the heat-treated condition, improvement began to be noted at temperatures slightly above 0° F.

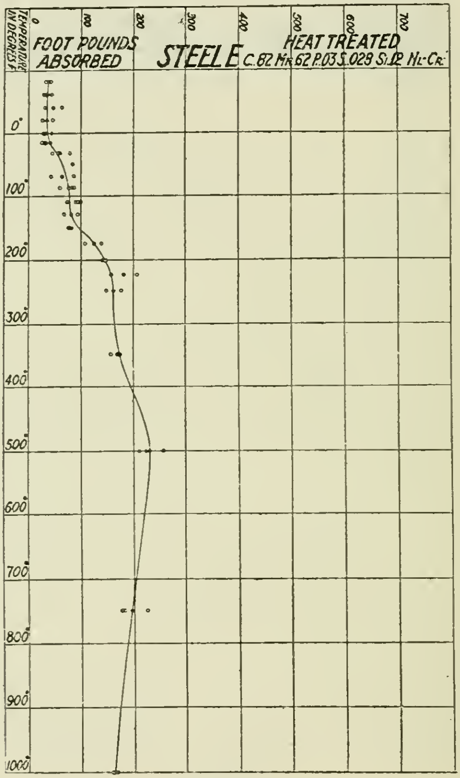


Fig. 17.

Figs. 18 and 19 are the consolidated curves previously referred to, prepared for the six steels examined in both the annealed and heat-treated conditions. Referring first to the consolidated curve for the steels in the annealed condition, the fact is evident that three curves do not show a decided upward tendency until a temperature was reached which was higher than in the case

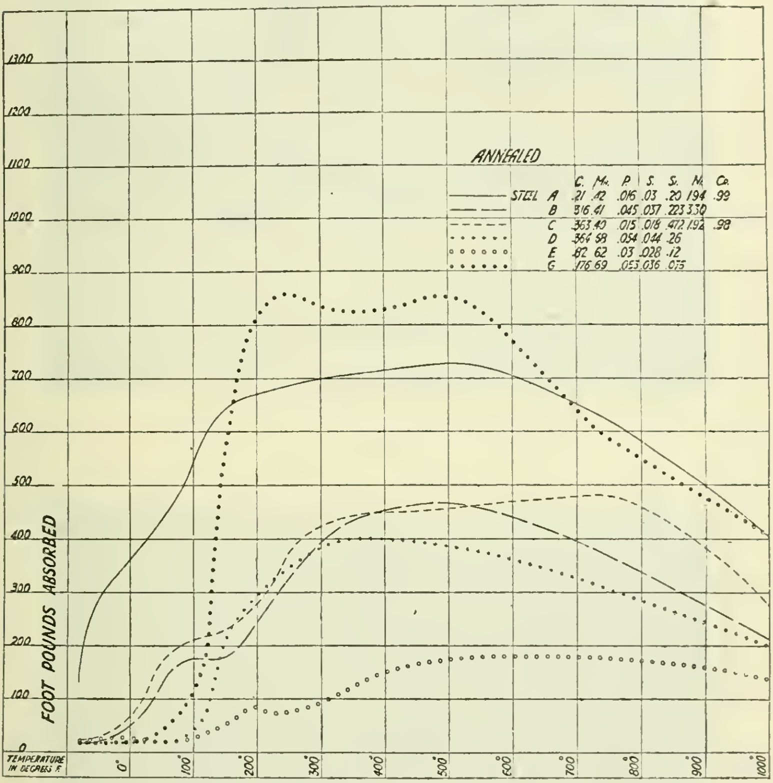


Fig. 18.—Consolidated Curves of Steels in Annealed Condition.

of the other three curves recorded on the same graph. Examining the composition of the steels represented by the three curves, which did not show the upward tendency until a higher temperature was reached, it will be found that they were all simple carbon steels. In the range 0° to 100° F., which can be considered as the working range of the majority of steels used in engineering structures, it will be noted that the three alloy steels gave uniformly higher values for resistance to impact than did the simple carbon steels. It has been pointed out by many authorities that it is not economical to use alloy steels in the annealed condition, and practically no advantages are obtainable thereby. It has been emphasised a great many times that alloy steels have their advantages and superior properties developed only by heat treatment, and therefore should only be used in the fabrication of parts where subsequent heat treatment is to be employed. It would appear from the curves herein presented that certain alloy steels have decided advantages in the annealed condition as regards resistance to impact.

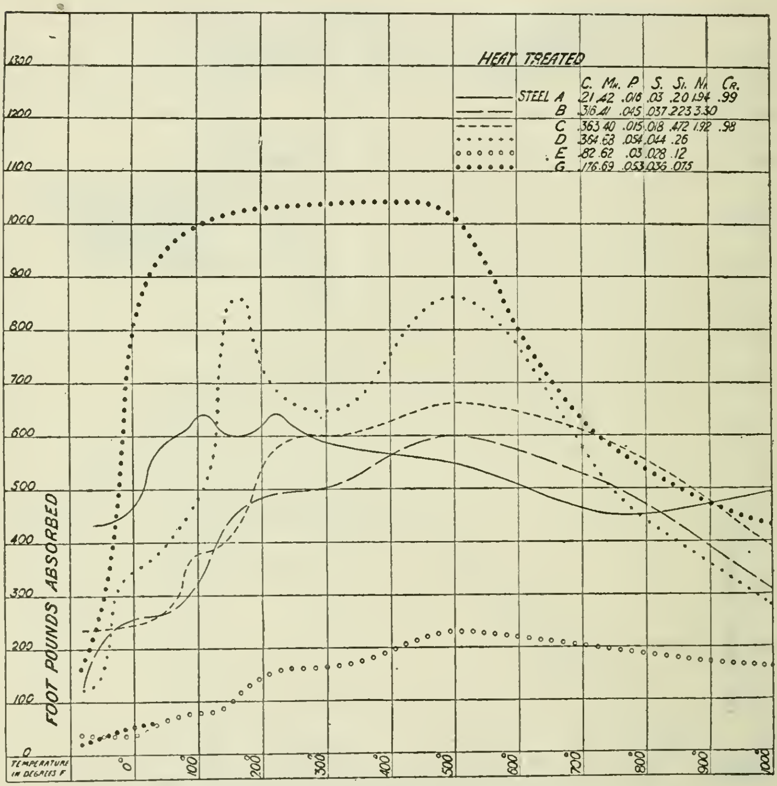
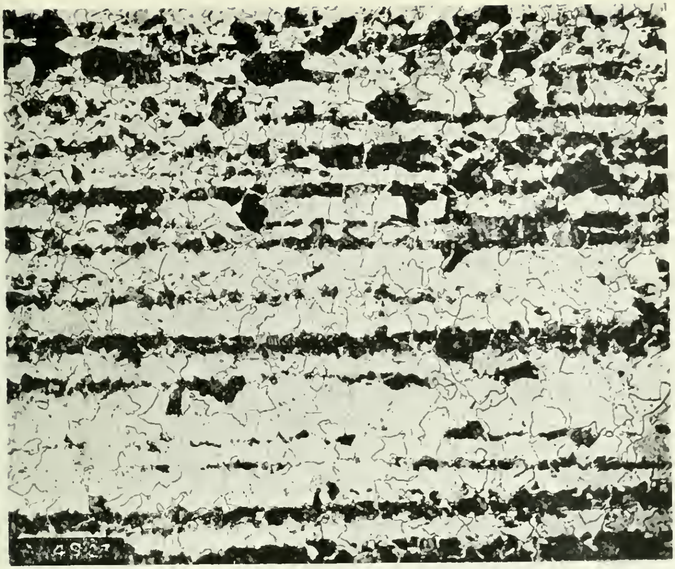
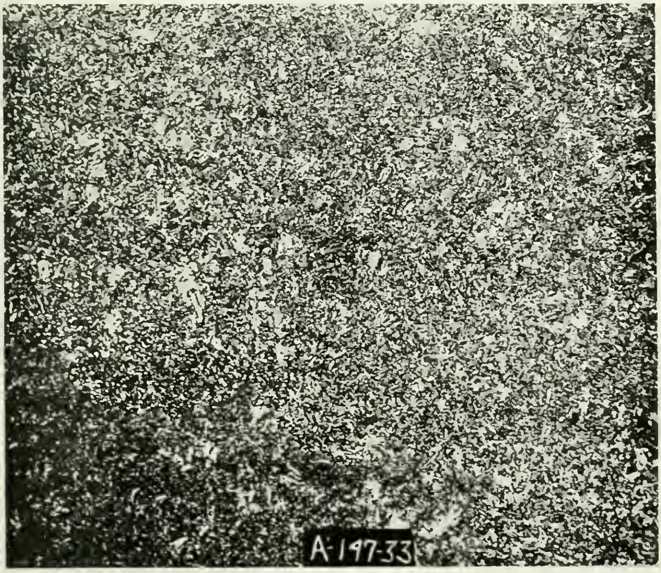


Fig. 19.—Consolidated Curves of Steels in Heat-treated Condition.

Referring to both consolidated curves, it will be noticed in some of them that there is a loop or falling off in the resistance

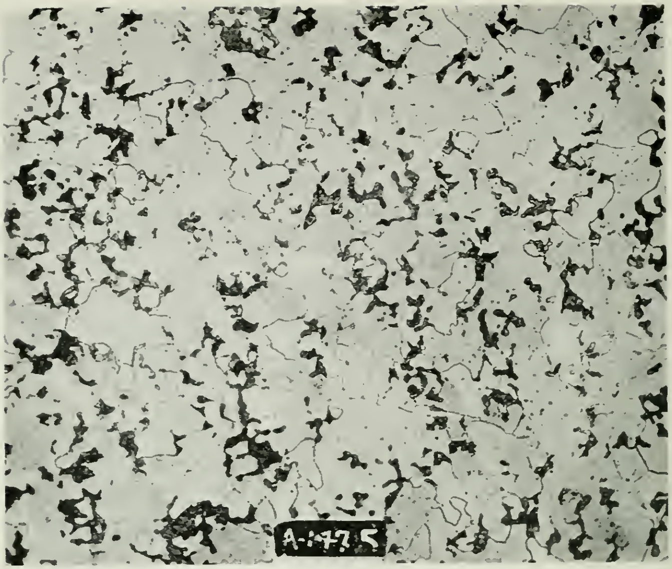


No. 1. Steel A in annealed condition.

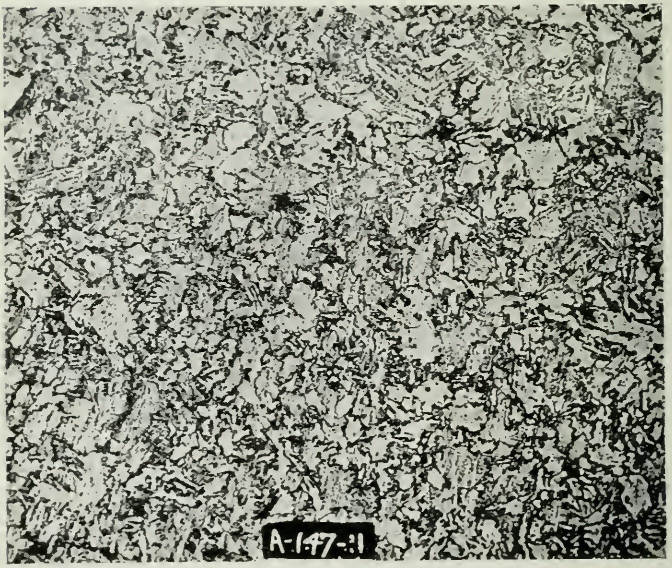


No. 2. Steel A in heat-treated condition.

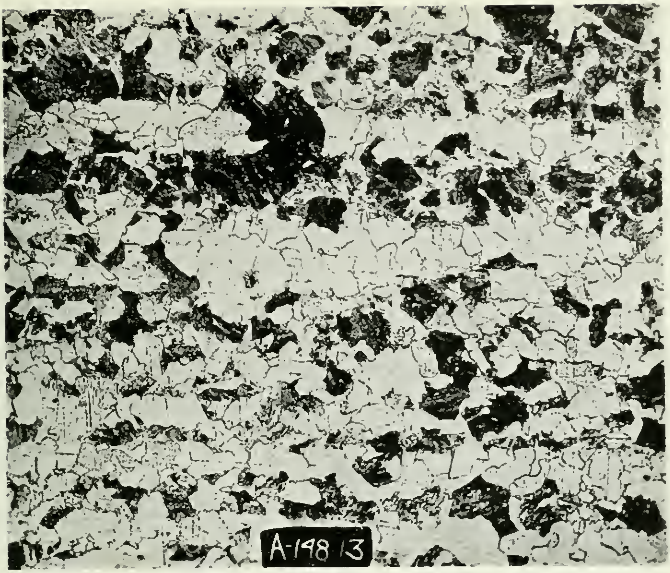
PLATE III.



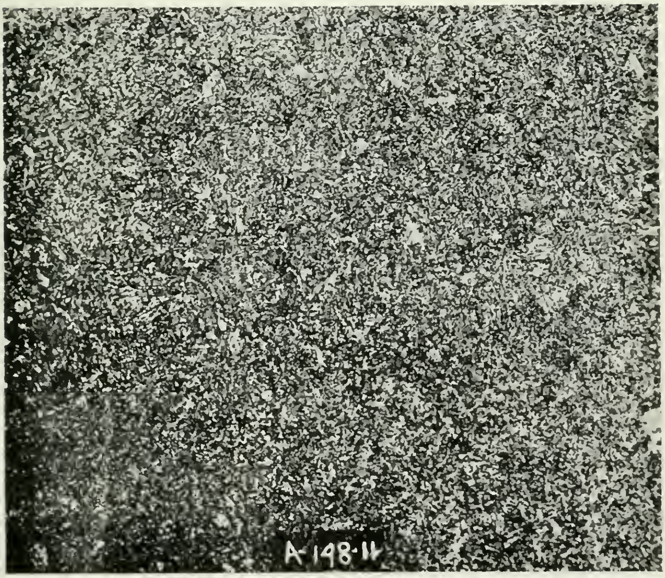
No. 3. Steel G in annealed condition.



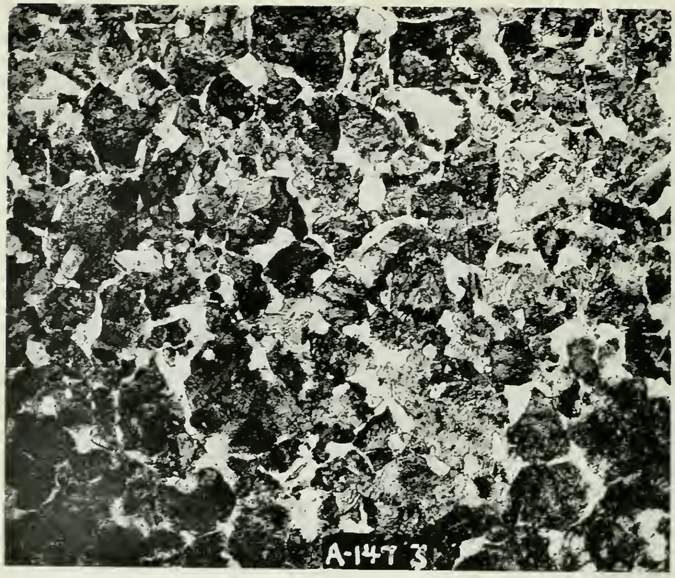
No. 4. Steel G in heat-treated condition.



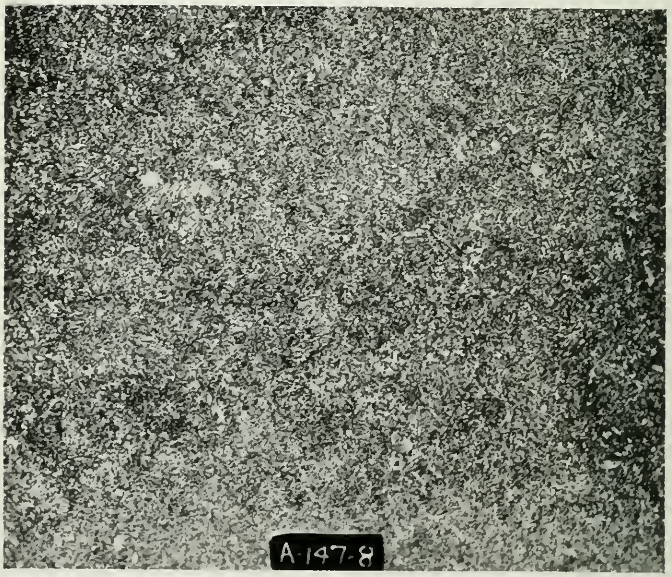
No. 5. Steel B in annealed condition.



No. 6. Steel B in heat-treated condition.

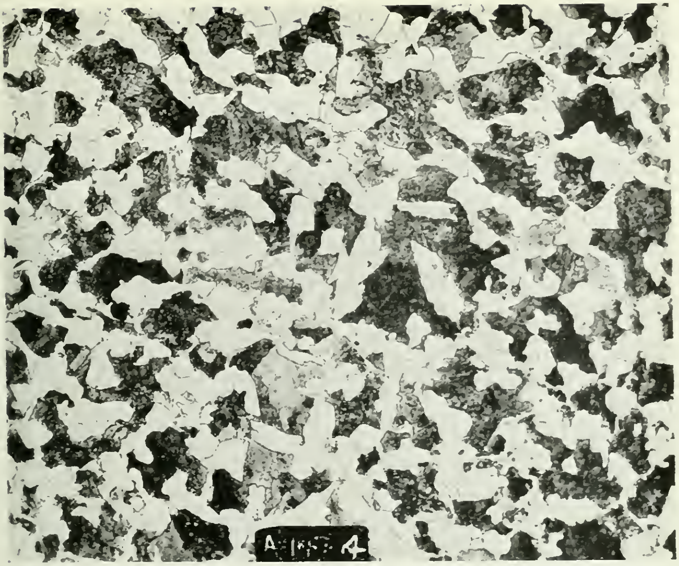


No. 7. Steel C in annealed condition.

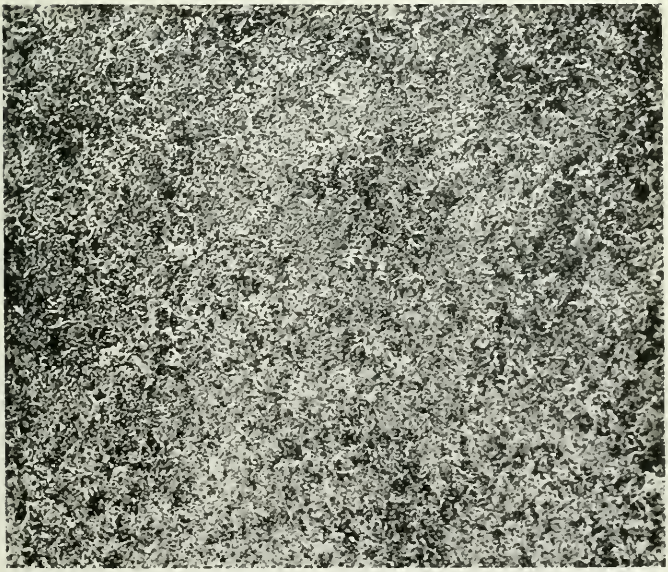


No. 8. Steel C in heat-treated condition.

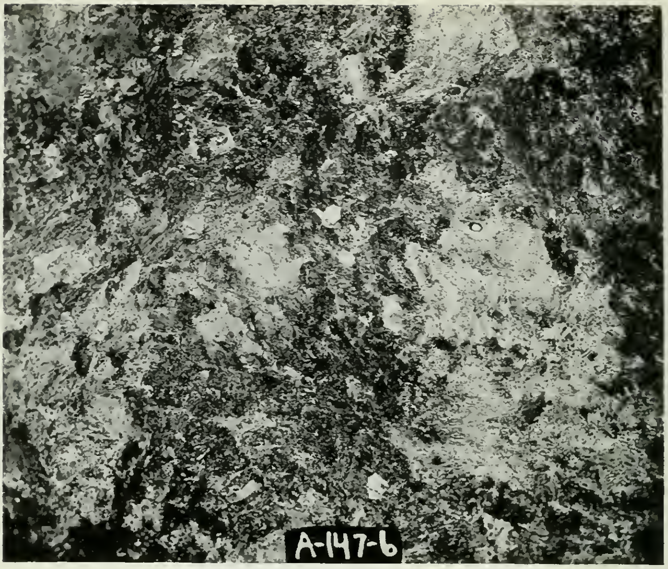
PLATE VI.



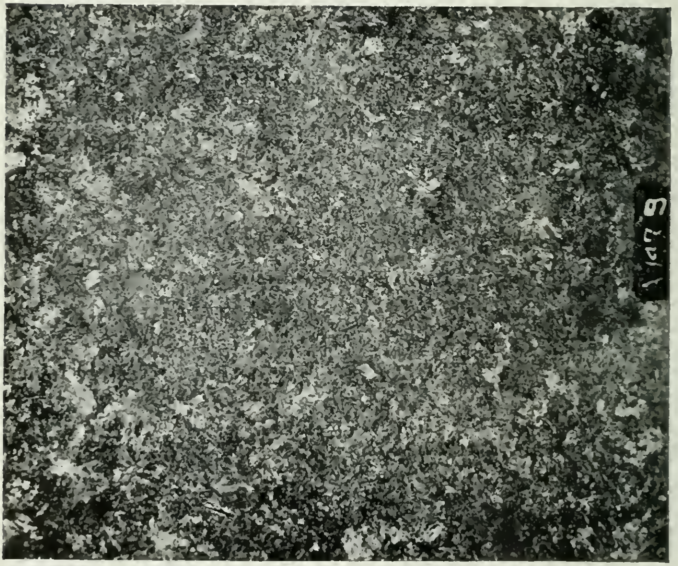
No. 9. Steel D in annealed condition.



No. 10. Steel D in heat-treated condition.

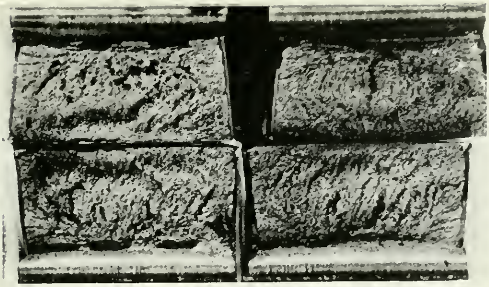


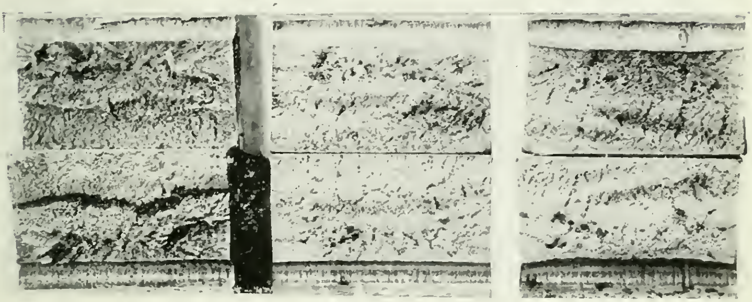
No. 11. Steel E in annealed condition.

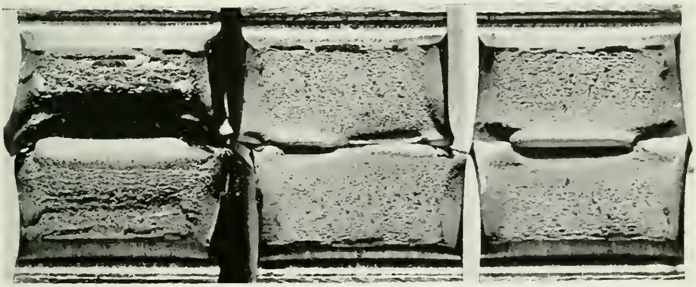


No. 12. Steel E in heat-treated condition.

PLATE VIII.


No. 13. A. –60° F. heat-treated.


No. 14. A. –80° F. annealed.


No. 15. A. 90° F. heat-treated.

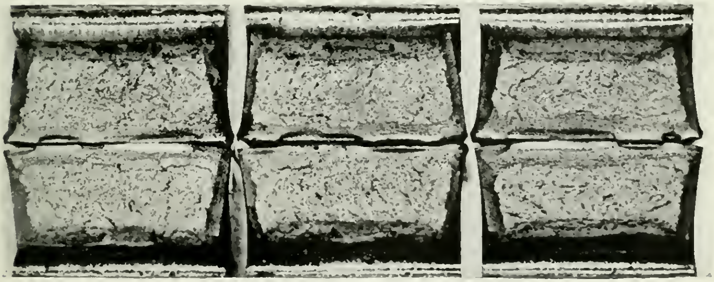
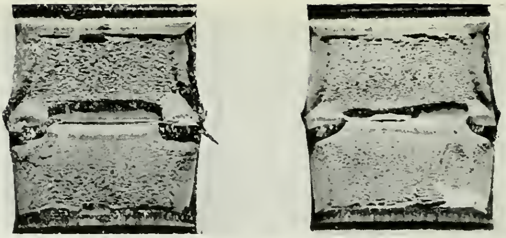
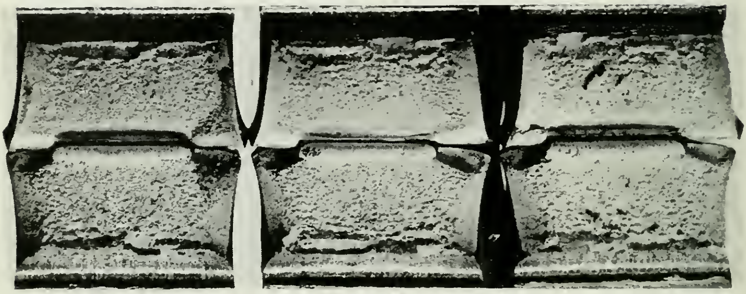

No. 16. A. 70° F. annealed.

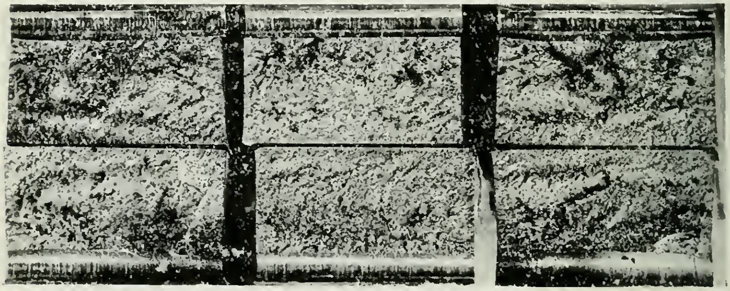
PLATE IX.



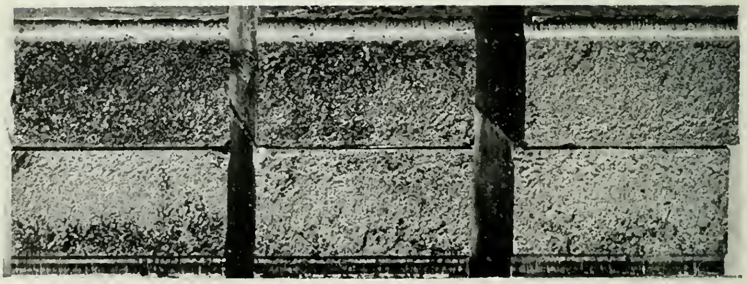
No. 17. A. 350° F. heat-treated.



No. 18. A. 350° F. annealed.

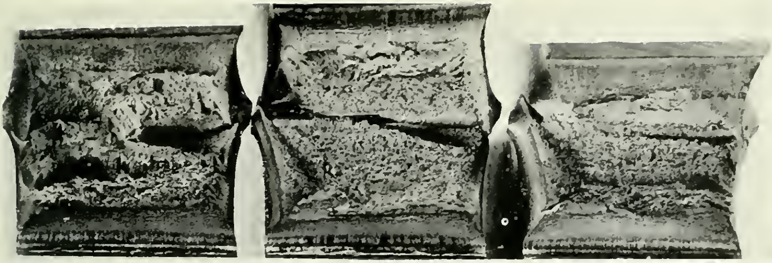


No. 19. G. −80° F. heat-treated.

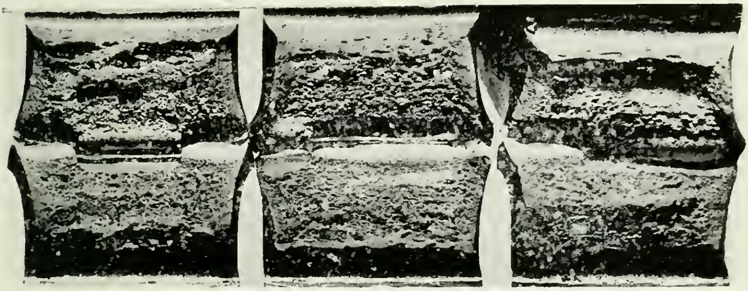


No. 20. G. −80° F. annealed.

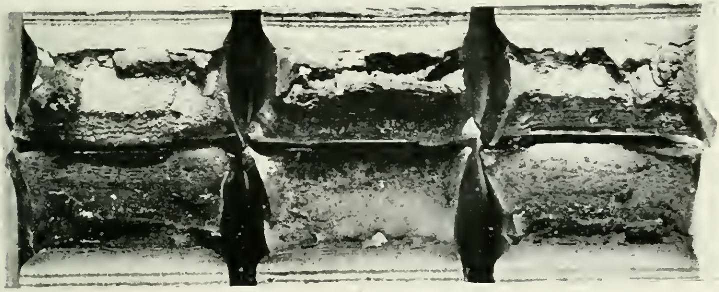
PLATE X.



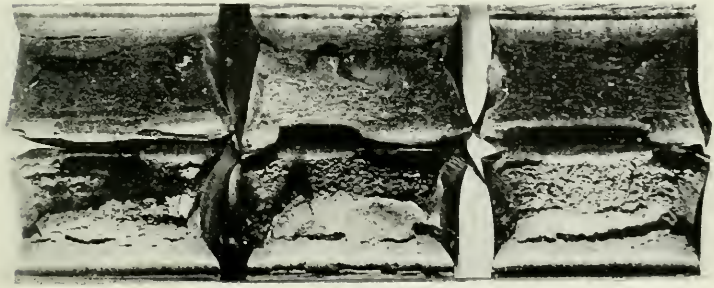
No. 21. G. 225° F. heat-treated.



No. 22. G. 225° F. annealed.



No. 23. G. 500° F. heat-treated.



No. 24. G. 500° F. annealed.

to impact in the range not far removed from 200° to 300° F. This is observable in several of the curves, and it is suggested that this effect was caused by the phenomenon commonly known as "blue brittleness." In an investigation earlier conducted by the author, it was found that all the phenomena of fracture in testing a notched specimen were exhibited in so short a period of time that the brittleness resulting from deformation in the "blue heat zone" was apparently unable to develop to any appreciable degree. Specimens deformed at a blue heat and tested at normal temperature by the notched-bar impact test clearly showed the brittleness resulting from deformation at a blue heat. Specimens of the same material, however, tested at a blue heat without previous deformation, did not show the same peculiarity to an appreciable degree. The general shape of some of the curves from material known to be susceptible to blue brittleness was not at all dissimilar to the shape of some of the curves in this report showing the loop in this region. For this reason it is suggested that the falling off of impact value in some of the instances was possibly due to the phenomenon of blue brittleness.

In concluding the discussion, it is desirable to give attention to the fractures exhibited by specimens tested at different temperatures. Considering first Steel A in the annealed condition, a decided crystalline fracture was obtained at −80° F., the crystalline appearance of the fracture beginning to disappear at 90° F. The fractures at 90° F. showed a crystalline centre with silky edges. At 350° F. the crystalline appearance of the fracture had completely disappeared. (See Plates VIII. and IX.)

In the case of Steel G in the annealed condition, a simple carbon steel of low carbon content, the fractures were crystalline up to a temperature of approximately 150° F. The fractures at this temperature showed a crystalline centre with silky edges. At 200° F. the centre of the fracture was still crystalline, the silky portion, however, being greatly increased. At 250° F. the crystalline appearance had entirely disappeared. (Plates IX. and X.)

The fractures of the other test specimens in the annealed condition could be discussed in detail in a similar manner, the general observation, however, being that the specimens broke with an entirely crystalline appearance, the amorphous or silky fracture first appearing on the outside of the test specimens and increasing in amount as the temperature of test increased, gradually replacing the crystalline appearance throughout the fracture. The various typical fractures in the annealed and heat-treated conditions for all the steels are included in this report.

Although not pertinent to this report, it is desired to state that the results obtained in this investigation have appeared to the author to be of sufficient practical application to warrant an extension of this investigation to steels of a more diversified range of composition. A number of steels have been selected and are now being subjected to tests on lines similar to those described in this report. It is hoped that the results can be submitted in a later report.

ACKNOWLEDGMENTS.

During the course of the experimental work outlined in this report, the author has had the entire co-operation and support of General C. C. Williams, Chief of Ordnance, United States Army, and General T. C. Dickson, Commanding Officer at Watertown Arsenal. The author wishes to acknowledge their support in this investigation, and to express his appreciation of their great interest and assistance.

The experimental work described in this report has been carried out almost entirely by Mr. N. Richardson, Research Engineer, and Mr. E. K. MacNutt, Research Chemist, at Watertown Arsenal. Many of the tests, particularly those at lower and higher temperatures, required long periods of uninterrupted work, and without the assistance of these gentlemen beyond their regular line of duty the data included in this report could not have been obtained.

In the compilation of the final report the greatest assistance has been rendered by Mr. N. Richardson, Mr. E. K. MacNutt, and Miss E. I. Atwood.

CORRESPONDENCE

Dr. L. AITCHISON (Birmingham) wrote that the amount of work that had been done in the investigation was enormous and the results obtained were very valuable. It seemed to be a pity that the author had used the Charpy notched specimen. There was little doubt that the Charpy machine was quite the most convenient one to use for such experiments as the author's, but there was no need to use the Charpy specimen. An Izod specimen, or a specimen of suitable dimensions bearing the Izod notch, could be used very conveniently. The superior discrimination exercised by the Izod notch was now well known and generally recognised—particularly when applied to materials of a brittle nature. In respect of the present work that applied particularly to the low temperature tests. The round Charpy notch was apt to smooth out differences in toughness that the Izod notch would discover. The effect of the notch was shown definitely in some experiments in which Dr. Aitchison had co-operated with Mr. Batson of the National Physical Laboratory. The matter under investigation was the effect of low temperatures upon the notched bar value of steel. It was found that some steels lost as much as 90 per cent. of their toughness when tested at —80° C. When tested without a notch the loss was only about 5 per cent. In all probability the Charpy value would be intermediate. He strongly urged, therefore, that as Mr. Langenberg proposed to continue his work he should use the Izod notch for the further tests. It was clear from all the known work that the toughness of most steels generally increased as the temperature rose, but that with many the toughness decreased as the temperature fell. The low temperature values were therefore of very direct importance, and more so than the high temperature results. It seemed important therefore to make all these tests, and particularly those at low temperatures, under the conditions that would lead to the most definite discrimination and therefore the greatest information.

With regard to the tests made at temperatures above normal, the author's curves appeared to indicate that at a temperature of about 1000° F. the toughness was falling away. Dr. Aitchison published[1] a number of tests made at high temperatures upon high chromium and high tungsten steels. About that temperature range a drop in the curve of toughness/temperature was indicated, but when the temperature was raised beyond that range the toughness values definitely and largely increased again. This fact should be noted in case a wrong conclusion was drawn from the author's results.

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[1] *Proceedings of the Institution of Automobile Engineers*, 1919, vol. 14, p. 31.

In tests made at low temperatures and reported to the Aeronautical Research Committee, Mr. Batson and Dr. Aitchison had examined a number of standard aeronautical steels down to — 80° C. The general result of those tests was to show that the hardened and tempered alloy steels retained a larger proportion of their toughness than was kept by the plain carbon steels whether hardened and tempered or normalised. That result did not quite fit in with the author's. The temperature employed was a little lower than the author's and the Izod notch was used. It would be interesting to see whether the latter difference affected the results materially.

Dr. R H. **Greaves** (Woolwich) wrote that he had been greatly interested in the results of the investigation in progress at Watertown Arsenal. Somewhat similar work was being carried out at Woolwich, though, in the case of steels, fewer tests had been made over the range 0–100° C. As regards the 3½ per cent. nickel steel, annealed and heat-treated, the general shape of the curve was in very good agreement with that found by the author. There was a maximum at 260° C. (500° F.) and a minimum at 600° C. (1112° F.), the heat-treated steel giving the higher figure at both temperatures.

At present there were only two points to which he desired to refer :

(1) The temperature coefficient of impact figure between (say) 0° and 200° F. was very dependent on heat treatment. Thus an overheated mild steel had a much steeper curve than the same steel in the normal condition (Fig. A). It rose from a lower figure at —18° C. (0° F.) to a far higher figure at 100° to 150° C.; both reached a minimum again at about 550° C. (1022° F.), and then rose rapidly as the temperature approached the critical point, the overheated steel still showing the higher figure. On the other hand, some mild steels showed an almost continuous fall in impact figure from 0° to 600° C. (32° to 1112° F.), followed by a rapid rise as the temperature of the critical range was approached.

The dependence of the temperature coefficient of impact figure on heat treatment was also illustrated by the case of nickel-chromium steels in the tough and temper-brittle condition (Fig. A). Attention had been called to this difference in behaviour by Monypenny.[1]

(2) The other point was in connection with the author's remarks on "blue-brittleness." Blue-brittleness was essentially a phenomenon of overstrain followed by elastic recovery proceeding at a rate comparable with the rate of increase of stress. The temperature at which the maximum embrittling effect appeared was higher the more rapid the deformation. The falling off in impact figure at 200° to 300° F. noted by the author might have some importance but had no connection with blue-brittleness which occurred at a higher temperature even when the deformation was comparatively slow. The general fall in impact figure to the right of the diagrams was, in the writer's

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[1] *Journal of the Iron and Steel Institute*, 1919, No. II. p. 398.

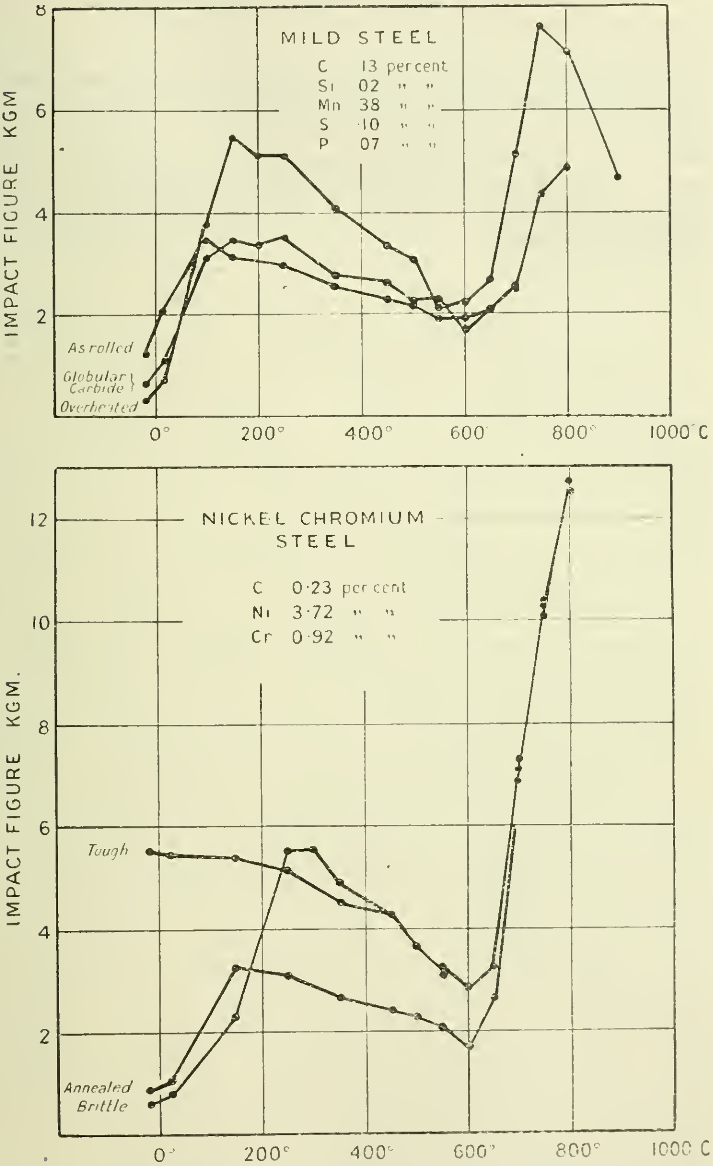

Fig. A.—Impact tests (average for each temperature) made on B.E.S.A. test-pieces in the 30-kilogramme Charpy machine.

opinion, the indication of blue-brittleness, but the temperatures used by the author were not high enough to show the maximum effect. A minimum impact figure was given by nearly all steels at 500° to 600° C. (932° to 1112° F.) under the conditions of test employed at Woolwich: stainless steels and high phosphorus carbon steels were exceptions. Within this range, the temperature of the minimum was lowest for Armco iron and highest for alloy steels. There was a big increase in impact figure at a slightly higher temperature, probably owing to the almost instantaneous occurrence of recrystallisation as deformation proceeded.

Carnegie Scholarship Memoirs, 1923.]

Iron and Steel Institute.

THE LOW APPARENT ELASTIC LIMIT OF QUENCHED OR WORK-HARDENED STEELS.

By LESLIE AITCHISON, D.Met., B.Sc., F.I.C.

The fact that certain steels, when tested in tension in the fully hardened state, give low values of the limit of proportionality has been known for quite a long time. Tensile tests executed with the refinement necessary to provide a true indication of the limit of proportionality have not been made with regularity, and in the absence of such tests the phenomenon would of course not be observed. The extended use of alloy steels just before the war, and the still greater use of them during the war in aircraft engines, together with the great increase in the number of accurate tests made upon hard steels, brought this property of hardened steels into comparative prominence. In particular, its occurrence came to be associated with the air-hardening nickel-chromium steels in their fully hardened state. It was observed also that the operation of tempering, although resulting in a lowering of the maximum stress of the steel, produced at the same time an increase in the value of the limit of proportionality up to a maximum. So far as the author is aware the observations on such steels were confined to those made during tensile tests.

The extended use of cold-worked steels in aircraft—particularly cold-worked steels with a fairly high maximum stress—for such parts as streamline wires, and metal spars formed from thin strip—brought about an extension of the critical testing done on these materials. As a result, it was found that such steels also, when fully hardened, had a low value of the limit of proportionality, and that this value was raised to a maximum by reheating or blueing. With the cold-worked materials, however, the reheating necessary to produce the maximum value of the limit of proportionality could be carried out at such a temperature as did not appreciably reduce the maximum stress.

There is considerable evidence that the low limit of proportionality in cold-worked steels is found almost universally—*i.e.*, in materials of very varying composition and constitution. In fact the lowering of the limit of proportionality by cold-working is by no means confined to steel, but occurs almost equally in most non-ferrous alloys. In respect of the steels hardened by quenching the property appears to be less widespread. It is perfectly certain, nevertheless, that the phenomenon is not in any way confined to air-hardening nickel-chromium steel. The similar behaviour of oil-hardening nickel-chromium steels is shown below. Low values for the limit of proportionality have also been observed in nickel steels and in some plain carbon steels, when these last have been hardened drastically—*i.e.*, to an extent that gives a structure in any way comparable with that obtained in the nickel-chromium steels. A plain carbon steel quenched from a moderately high temperature and in a sample of small diameter, gives the same kind of result.

The fairly widespread incidence of this quality amongst quenched steels can be inferred from a critical study of the values returned for the yield point of such material. It is extremely doubtful whether quenched materials (of a high maximum stress particularly) have a yield point, properly so called. What is generally observed as the yield point in a tensile test upon such material is the stress value at which the total strain has become appreciably or measurably large. This stress must almost necessarily be higher than the limit of proportionality, and it is not entirely absurd to imagine that there is some general relationship between the limit of proportionality and this fictitious yield point. There is certainly no definite relationship, as will be shown later, but there is almost certainly the general relationship that the steel with the higher limit of proportionality possesses the higher yield point, so called. Tests carefully made and recorded do show generally that the so-called yield point in fully quench-hardened alloy steels (and others) is lower than in the same steel after quenching and reheating to say 200°, 300°, or 400° C. This observation suggests that the existence of a low value of the limit of proportionality in quench-hardened steels is more widespread than has been imagined.

It has been considered that the low limit of proportionality in the quench-hardened alloy steels was a serious disadvantage in regard to the employment of such steels in engineering, and steps were often taken to permit their incorporation in structures only after tempering at a temperature sufficiently high to produce in the steel a fairly high limit of proportionality. This precaution is probably not really necessary, as the low limit of proportionality of the particular class of steel is affected, not only in tempering, but by mechanical stresses and especially fatigue stresses, as will be shown later. As the vast majority of parts made from such steels are exposed to fatigue the value of the limit of proportionality may be raised to a safe value.

In the interpretation of the low limit of proportionality in the cold-worked steels this saving condition probably does not apply with equal force, simply because such steels are very often used in circumstances which do not permit of the full operation of the beneficent effects of fatigue, if any occur. The investigator is assured by competent observers that the detrimental effect of the low limit of proportionality is experienced in the behaviour of structural members of aircraft that have been built up from cold-worked steel strip. The primary failure of such members occurs at a lower stress when the steel from which they are made is fully work-hardened than when its limit of proportionality has been raised by blueing.

The existence of the low limit of proportionality has generally been explained in the same way for both the kinds of steel in which it has been observed. It has generally been stated that the low value is purely a reflection of strains locked up in the metal during hardening. These strains are released during the progress of the tensile test, with the consequent appearance of a kink in the load/extension curve. This explanation is held to apply to steels hardened either by quenching or by cold working. Such an explanation seems difficult to accept, and although it probably contains the germ of truth can hardly be regarded as a full and complete account of the phenomenon. The objections that can be urged against it appear more powerfully in regard to the quenched steels than the cold-worked steels. One powerful difficulty with regard to a simple quenching strain hypothesis is seen in the fact that the limit of proportionality has a very fairly regular value in any one particular steel when hardened by quenching—whether it is quenched in a complicated or in a simple shape, and whether air-hardened (if of that type) or hardened by quenching in oil. Undoubtedly, the nett magnitude of the hardening strains in a piece of steel is influenced by its form, but apparently the limit of proportionality of the steel is not influenced accordingly. A second difficulty is seen in the fact (which is indubitable) that quenching strains as such are set up and produced in the quenching of quite mild steels, and yet such steels do not appear to be affected in respect of their limit of proportionality (at any rate to no measurable extent).

Every steel which shows a really low ratio between the limit of proportionality and the maximum stress is found to have been hardened, and this fact alone suggests that there is a close association between the low value of the limit of proportionality and the *instability* of the steel, which is brought about in consequence of the hardening operations. It is not to be assumed, however, that the instability in all hardened steels is identical in nature, or produced in the same measure, and therefore there appears to be no reason to imagine that the low limit of proportionality in all such steels is due to the same cause. In a work-hardened steel the instability may be of two kinds. During the process of working, the constituent crystals of the steel have been distorted and plastically moulded. This can only have been brought about by a considerable amount of slipping over gliding planes within the crystals, which has resulted in the constituent crystals of the steel assuming quite a new and different external shape. In addition to this large and visible change, the interior of each crystal has been changed by the formation of gliding planes and the quasi-elastic distortion of the crystalline material lying between the gliding planes, with the result that each individual crystal is in an unstable condition. The ferrite is strained and may probably be held in this condition of more or less elastic strain by reason of the stiffening effect of the gliding planes and the new conformations of the crystals in the material. When a cold-worked steel is reheated, the first effect is likely to be felt within the individual crystal, on the material composing the gliding planes. There will be a tendency for the ferrite to rearrange itself in the way which will best produce within it an unstrained condition. Heating to a much higher temperature is necessary in order to cause the steel to recrystallise sufficiently to rid itself completely of the plastic strain. This is achieved by the breaking up of the strained crystals, followed by a regrouping in a crystalline form which may be regarded as being as completely unstrained as possible.

The suggestion has frequently been made that austenite may be produced in a cold-worked steel during the work-hardening operation. This would involve the allotropic transformation of some of the alpha iron to the gamma state, and therefore a change of some crystals from a cube-centred cubic lattice structure to that of a face-centred cubic lattice. If such a change did take place, the cold-worked steel would approximate a little more nearly in constitution to the quenched steels. It does not, however, seem probable that such a transformation is brought about, and certainly no such change seems to be necessary in order to account for the properties of the work-hardened metal. It is to be noted in connection with this possible change that Bürger has examined thin drawn wires and found that the space lattice of the material was not altered by such drastic working, although the 110 planes are preferably brought into a specific position relative to the axis of the wire. This, however, is quite different from a change in the lattice.

A steel that has been hardened by quenching is unstable in a different way. The type of instability in such a steel depends largely upon its composition, upon the temperature from which the steel has been quenched, upon the speed of quenching, and also the relationship between these three factors. At temperatures above the upper critical point all steels are in the austenitic condition. Comparatively few steels completely retain this condition when they are cooled either rapidly or slowly. In the majority of steels martensite is the result of quench hardening. In the alloy steels, however, it is reasonably certain that quenching does not produce a complete change to the martensitic condition. In other words, a certain proportion of the iron remains in the gamma condition. The actual proportion of such iron present in the steel may be very small, but if any is there, the steel contains an element of considerable instability.

There will always be a powerful tendency for any austenite present in the average hardened nickel-chromium steel to change at least into the martensitic condition, just as there is a tendency for the martensite to change to the troostitic, sorbitic, or even pearlitic condition, a change which occurs rapidly when circumstances are favourable. An alteration from austenite to martensite is accompanied by an expansion. The suppression of the expansion in the steel during, and by, the operation of quenching will tend to restrain the austenite and to prevent it from changing as completely as possible into martensite. Any event, therefore, which results in the removal of the pressure will assist in the alteration from the austenitic to the martensitic state.[1]

The production of austenite by quenching is not by any means confined to alloy steels. In a plain carbon steel containing a fairly high proportion of carbon it is possible to obtain austenite in considerable quantities by merely quenching the metal in water from a fairly high temperature. It is easy to imagine, therefore, that in many steels which are quenched drastically a certain amount of austenite is likely to be produced. In those alloy steels, which have a composition approximating to that suitable for the production of "cold" austenite, the probability of the presence of austenite in the steel in appreciable quantities after quenching is considerably greater. The existence of the austenite definitely indicates variable pressure and strain, and therefore instability.

The last type of instability may, therefore, be regarded as common to all those hardened steels which have been either quenched drastically, or which, by an easier process of hardening, have hardened to a very high value of maximum stress. The high tensile strength is of course in itself an indication that the steel largely consists of martensite. The formation of martensite during cooling, however, necessarily means the creation of a strong and rigid constituent which can exercise a notable pressure upon the residual material and therefore tend to preserve a certain proportion of it in the austenitic condition. If, therefore, any portion of the steel is constrained (*e.g.*, from the outside), the actual expansion of a proportion of the austenite of this portion of the metal into the martensitic condition in itself tends to increase the pressure upon the remaining austenite, and thereby tends towards the preservation of some at least of this residual austenite in its unchanged condition.

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[1] Amongst others see Andrew, Ripper, Miller and Wragg, *Journal of the Iron and Steel Institute*, 1920, No. I.; and Aitchison and Woodvine, *ibid.*, 1922, No. II. p. 175.

Regarded in this way quenched steels are therefore both unstable and in a state of strain. If the strained condition of hardened steels, which has been referred to above as purporting to provide an explanation of the low limit of proportionality, be regarded in the way that has just been described, it is likely that the state of strain in the steel may be found to provide an explanation of the low limit of proportionality. It is quite possible, however, that the low limit of proportionality in a quenched steel may be due to some constitutional condition of the material rather than to the mere fact that the steel is somewhat strained, although there may be some relationship between the state of strain in the metal and the particular constitutional condition referred to.

It should be clear, therefore, that although the low limit of proportionality of a hardened steel is a good indication of a marked instability in that material, this instability is not necessarily the same in all kinds of steel, and further that it is unlikely in particular that the low limit of proportionality in cold-worked steels and in quenched steels can be referred to the same cause.

In carrying out the examination of steels which have a low limit of proportionality as much attention as possible has been paid to the practical significance of that phenomenon. For this reason an investigation has been made of the effect, if any, of the low limit of proportionality upon the fatigue strength of the steel in the different conditions and also upon the corresponding values of the proof stress. In the majority of instances the fatigue range of a steel is of much greater importance than any other mechanical property which the material may possess. For the purpose of inspection (*i.e.*, acceptance and rejection) of material for engineering purposes, as well as for the requirements of design, the proof stress is exceedingly valuable. The extent to which these two properties are affected by the low limit of proportionality is, therefore, in one way a measure of the importance of this property. If it does not affect either of them appreciably, it is a property that can be neglected for many of the purposes to which the steels which possess it may be put. An examination of the incidence and vagaries of this property may also bring to light some information upon the very important question as to whether or not this primitive elastic limit of steel has any significance whatever, or whether it is not a phenomenon whose numerical value is very largely fortuitous and unimportant.

Experimental Materials.

For the bulk of the experiments in regard to the phenomena under investigation five materials have been employed. These were respectively :

A. A nickel-chromium steel, that when cooled in air hardens to a maximum stress of over 100 tons per square inch. This steel was used in the form of rolled bar.

B. A different nickel-chromium steel of the same type as steel A, but which was used in the form of rolled strip.

C. A nickel-chromium steel of the type usually heat-treated by hardening in oil. This steel was also used in the form of rolled bar.

D. A medium carbon steel rolled in the form of bar and cold drawn extensively to give a fairly high maximum stress.

E. A steel similar to steel D, but cold rolled extensively in the strip form to give a high maximum stress.

The steel A was obtained in round bars, part of 1 inch diameter and part of $\frac{3}{4}$ inch diameter. The steel B was supplied as flat bars $1\frac{1}{2}$ inch by 0·160 inch thick (8 s.w.g.). The steel C was obtained in round bars $\frac{3}{4}$ inch diameter, and steel D 1 inch in diameter. The steel E was supplied in strip of dimensions $1\frac{1}{4}$ inch by $\frac{1}{8}$ inch.

The chemical compositions of all these materials are shown in Table I. :

Table I.—*The Chemical Analyses of the Experimental Materials.*

Steel.	A.	B.	C.	D.	E.
Carbon per cent.	0·34	0·29	0·36	0·66	0·66
Silicon ,,	0·18	0·29	0·15	0·06	0·07
Manganese ,,	0·60	0·49	0·73	0·67	0·66
Sulphur ,,	0·041	0·014	0·037	0·019	0·019
Phosphorus ,,	0·037	0·027	0·032	0·028	0·027
Nickel ,,	4·70	4·68	3·70	nil	nil
Chromium ,,	1·54	1·01	0·90	nil	nil

The analyses in Table I. show that the steels employed are of normal composition, and that they are such materials as are met with regularly in the ordinary course of commercial practice.

MECHANICAL TESTS.

The simplest series of tests to consider are those which indicate definitely the nature of the incidence of the phenomena that are to be investigated. Such tests involve the tensile and compressile properties of the various steels in the fully hardened condition and also after reheating to different temperatures (tempering in the treatment of the nickel-chromium steels, and blueing in the treatment of the cold-worked steels). It may simplify the consideration of the values obtained for the limit of proportionality and proof stress if an exhibition is first made of the changes of maximum stress experienced by the different materials when heat-treated at various temperatures in the ways described. The maximum stress of a steel is generally the most widely known mechanical property of the material, and is the one that is usually current in the minds of those who are considering the steel. In Table II. the maximum stress

TABLE II.—*The Effect of Tempering at Different Temperatures upon the Maximum Stress in Tension of Air-hardened Nickel-Chromium Steel Bar A.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Maximum Stress. Tons per Sq. In.
ATA1	830	...	110·25
ATA2	830	...	110·5
ATA3	830	100	102·4
ATA4	830	100	102·2
ATA5	830	200	95·4
ATA6	830	200	97·5
ATA7	830	300	92·5
ATA8	830	300	92·0
ATA9	830	400	84·5
ATA10	830	400	83·7
ATA11	830	500	70·5
ATA12	830	500	69·5
ATA13	830	600	60·5
ATA14	830	600	60·7

values in tension of steel A are shown when it is in the fully hardened condition and after it has been tempered at different temperatures, whilst in Tables III. and IV. are the corresponding values for steels B and C. In Tables V. and VI. are shown the maximum stress values in tension of the cold-worked steels D and E when in the fully cold-worked state, and after they have been blued at different temperatures.

TABLE III.—*The Effect of Tempering at Different Temperatures upon the Maximum Stress in Tension of Air-hardened Nickel-Chromium Steel Strip B.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Maximum Stress. Tons per Sq. In.
BTA1	830	...	112·4
BTA2	830	...	112·0
BTA3	830	200	109·6
BTA4	830	200	109·2
BTA5	830	400	85·8
BTA6	830	400	87·4
BTA7	830	600	62·8
BTA8	830	600	64·1

TABLE IV.—*The Effect of Tempering at Different Temperatures upon the Maximum Stress in Tension of Oil-hardened Nickel-Chromium Steel Bar C.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Maximum Stress. Tons per Sq. In.
CTA1	830	...	122·6
CTA2	830	...	124·2
CTA3	830	100	120·3
CTA4	830	100	121·8
CTA5	830	200	109·9
CTA6	830	200	111·1
CTA7	830	300	99·3
CTA8	830	300	101·7
CTA9	830	400	91·7
CTA10	830	400	92·8

The method of heat treatment employed for the steels of each type was kept constant. The nickel-chromium steels were machined to the test-piece size plus a grinding allowance, and then hardened from the temperature recorded in the table. They were then reheated to the selected tempering temperature, maintained at that temperature for half an hour and allowed to cool in the air. The fully heat-treated specimens were then brought

TABLE V.—*The Effect of Blueing at Different Temperatures upon the Maximum Stress in Tension of Cold-worked Steel Bar D.*

Mark.	Reheating Temperature. ° C.	Maximum Stress. Tons per Sq. In.	Elongation per Cent.	Reduction of Area per Cent.
DTA1	...	61·1	6·25	14·9
DTA2	...	60·6	7·5	19·5
DTA3	100	59·4	8·0	23·3
DTA4	100	57·8	9·0	25·6
DTA5	200	57·8	8·0	25·5
DTA6	200	56·7	10·0	30·2
DTA7	300	60·5	10·5	26·6
DTA8	300	60·0	10·0	26·8
DTA9	400	58·4	12·0	27·7
DTA10	400	58·3	11·5	27·3
DTA11	500	52·1	16·0	31·4
DTA12	500	53·0	16·5	32·6
DTA13	600	40·2	31·5	48·3
DTA14	600	40·6	31·5	48·2

TABLE VI.—*The Effect of Blueing at Different Temperatures upon the Maximum Stress in Tension of Cold-worked Steel Strip E.*

Mark.	Reheating Temperature. ° C.	Maximum Stress. Tons per Sq. In.	Elongation per Cent. (1 in.).
ETA1	...	67·2	2·2
ETA2	...	62·4	2·0
ETA3	100	63·2	2·2
ETA4	100	63·1	2·5
ETA5	200	62·1	3·0
ETA6	200	63·0	3·75
ETA7	300	66·1	2·5
ETA8	300	62·8	2·75
ETA9	400	63·1	5·0
ETA10	400	63·8	4·9
ETA11	500	57·7	9·5
ETA12	500	57·6	9·75
ETA13	600	37·7	24·5
ETA14	600	40·1	21·5

to the finished size either by grinding or by machining, these operations being carried out with the maximum care possible and with the least violence in the disturbance of the surface of the metal. The cold-worked bars and strips were heat-treated by being maintained at the specified temperatures for half an hour, and they likewise were cooled in the air from the blueing temperatures. The specimens from the cold-worked steels were treated in the full size of the bar or strip, and the test-pieces were machined subsequently from the treated specimen—care always being exercised to avoid the introduction of machining strains as far as possible. The strip test-pieces, both of the alloy and the plain carbon steels, were protected against decarburisation of the skin during the heat-treatment process by coating them with N.C. paint (prepared by The Amalgams Co., Sheffield), such as is used to prevent carburisation during the case-hardening process.

The maximum stress results shown in Tables II. to VI. are quite normal and usual, and call for no special comment. Unless otherwise stated the elongation per cent. is calculated on a gauge length, $L = 4\sqrt{\text{area of section}}$.

In the determination of the limit of proportionality of the specimens no unusual method was adopted. The most important precaution was to ensure that perfect axial loading of the test-pieces was secured. (This precaution, of course, was also adopted in making the maximum stress tests.) For the circular specimens the form of shackle that was used was substantially that designed by Professor A. Robertson, the actual form employed being shown in Fig. 1. Repeated tests and prolonged experience of this type of shackle have shown quite convincingly that the accuracy of the axial loading secured by such device is perfectly satisfactory. For the strip testing a modification of the same shackle was used, the form in use being depicted in Fig. 2. In this modification the principle of the ball joint is adhered to, but a special mode of gripping the specimen had to be resorted to. Friction grips were used, but the wedges used to secure the specimens in position were made of such a form that the butt end of the test specimen was accurately and not fortuitously placed between them, and so that the axis of the test specimen coincided with the axial line of the shackle through the ball joint. The results of the very large number of tests made with these shackles

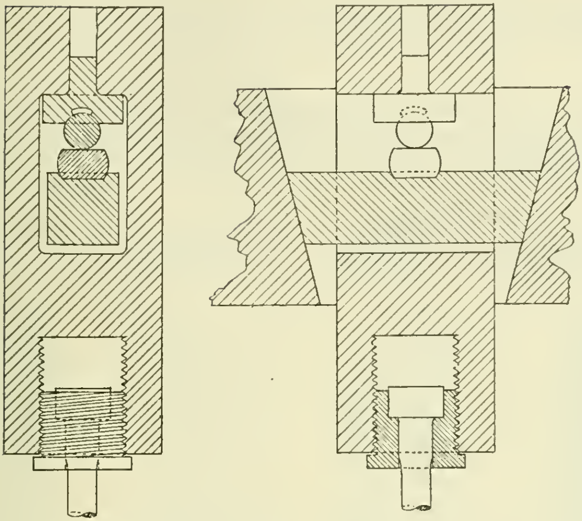

Fig. 1.—Axial loading shackles used for circular specimens.

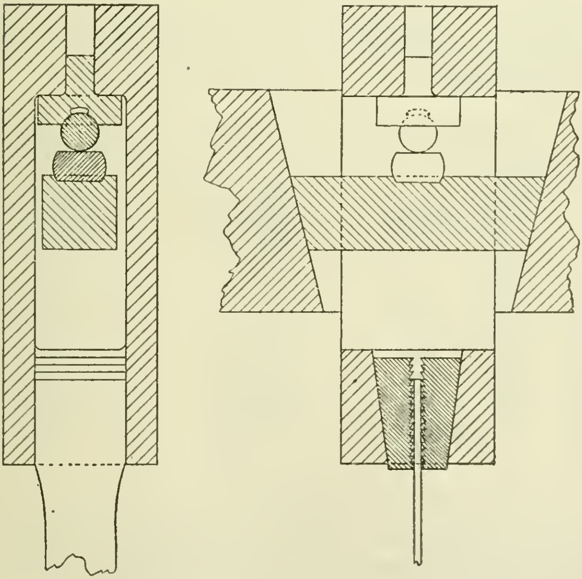

Fig. 2.—Axial loading shackles used for strip specimens.

(including numerous routine tests on the hard strip steels) have demonstrated their reliability and excellence. These axial loading shackles were employed for all the tests—whether for limit of proportionality, proof stress, or maximum stress.

Table VII.—*The Limit of Proportionality in Tension of Air-hardened Nickel-Chromium Steel Bar A before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
ATB1	830	...	24·6
ATB2	830	...	24·1
ATB3	830	100	35·4
ATB4	830	100	35·4
ATB5	830	200	58·5
ATB6	830	200	60·5
ATB7	830	300	67·5
ATB8	830	300	64·5
ATB9	830	400	58·5
ATB10	830	400	57·9
ATB11	830	500	55·1
ATB12	830	500	56·0
ATB13	830	600	37·9
ATB14	830	600	39·7

Table VIII.—*The Limit of Proportionality in Tension of Air-hardened Nickel-Chromium Steel Strip B before and after Tempering.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
BTB1	830	...	13·2
BTB2	830	...	12·9
BTB3	830	200	25·7
BTB4	830	200	25·7
BTB5	830	400	57·9
BTB6	830	400	57·9
BTB7	830	600	35·6
BTB8	830	600	36·7

For the determination of the load/extension diagrams an extensometer of the usual type was employed. It was one specially constructed, and gave direct readings to one tenthousandth of an inch. The suitability of this instrument can be gathered from an inspection of the various load/extension diagrams that are shown herein.

TABLE IX.—*The Limit of Proportionality in Tension of Oil-hardened Nickel-Chromium Steel Bar C before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
CTB1	830	...	25·6
CTB2	830	...	27·9
CTB3	830	100	33·2
CTB4	830	100	32·9
CTB5	830	200	58·0
CTB6	830	200	56·4
CTB7	830	300	70·1
CTB8	830	300	70·6
CTB9	830	400	64·7
CTB10	830	400	64·8

TABLE X.—*The Limit of Proportionality in Tension of Cold-worked Steel Bar D before and after Blueing at Different Temperatures.*

Mark.	Reheating Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
DTB1	...	23·3
DTB2	...	24·9
DTB3	100	24·2
DTB4	100	23·1
DTB5	200	30·7
DTB6	200	29·1
DTB7	300	42·4
DTB8	300	42·5
DTB9	400	42·3
DTB10	400	42·2
DTB11	500	42·4
DTB12	500	40·8
DTB13	600	24·2
DTB14	600	23·9

It is convenient to show first the results of the determinations of the limit of proportionality made upon the different steels under investigation, in the fully hardened condition (produced either by heat treatment or by cold working), and also after reheating to various temperatures. The alteration of the limit of proportionality has been examined both in tension and in compression. The tension values can be given first. These have been obtained upon all the five steels described above. The results given by the air-hardening steel bar A are shown in Table VII., those for the air-hardening steel strip B in Table VIII., for the oil-hardening steel bar C in Table IX., for the cold-worked steel bar D in Table X., and for the cold-worked steel strip E in Table XI. In addition to the values given in the tables, a selection of the load/extension diagrams are given in Figs. 3 and 4.

TABLE XI.—*The Limit of Proportionality in Tension of Cold-worked Steel Strip E before and after Blueing.*

Mark.	Reheating Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
ETB1	...	23·0
ETB2	...	25·2
ETB3	100	31·4
ETB4	100	33·3
ETB5	200	37·3
ETB6	200	38·8
ETB8	300	44·6
ETB10	400	41·9
ETB11	500	36·1
ETB12	500	37·6
ETB13	600	26·0
ETB14	600	30·0

The test values set out in Tables VII. to XI. show clearly that the limit of proportionality in all these steels when fully hardened (either by heat treatment or by cold work) is low. The effect of reheating to a comparatively low temperature is to raise the value of this property. Successive increases in the reheating temperature bring about corresponding successive increases in the value of the limit of proportionality until a maximum is reached, after which a further increase in the reheating temperature induces a fall in the value of the limit of proportionality. The results of the duplicate tests are shown for all the steels, and it is desirable to note at once that there is a close similarity in the actual values recorded by the duplicate specimens. This notice is not called for as a tribute to the accuracy of the testing, but to draw attention to what constitutes an indication that the phenomena under observation are of regular occurrence and are not fortuitous apparitions, the actual values of which are of no significance. This matter will be referred to again *infra.*

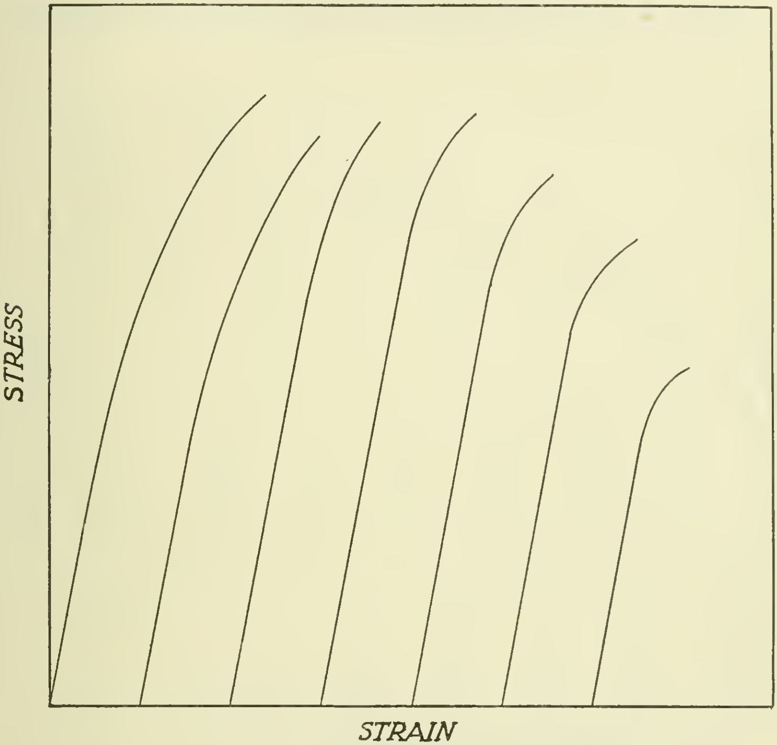

Fig. 3.—Series of load/extension curves taken from air-hardened steel bar as hardened and after tempering at temperatures from 100° to 600° C.

The alterations in the value of the limit of proportionality of two typical steels—one quench hardened and the other cold worked—brought about by reheating to various temperatures, are depicted in Figs. 5 and 6. The curves in Figs. 5 and 6 show that the general trend of the effect upon the limit of proportionality of reheating a hardened steel is the same in a steel that has been hardened by heat treatment and in one that has been hardened by cold work. This, however, does not necessarily mean that either the original low value of this property or the effect of reheating in raising this value can be referred to the same cause in the two kinds of steel. In each steel the value of the limit of proportionality rises to a maximum after reheating to a temperature round about 400° C. It is to be noted that the temperature of reheating that corresponds to the maximum value of the limit of proportionality is the same (approximately) for all the three kinds of nickel-chromium steel, whether they have been hardened in air or in oil.

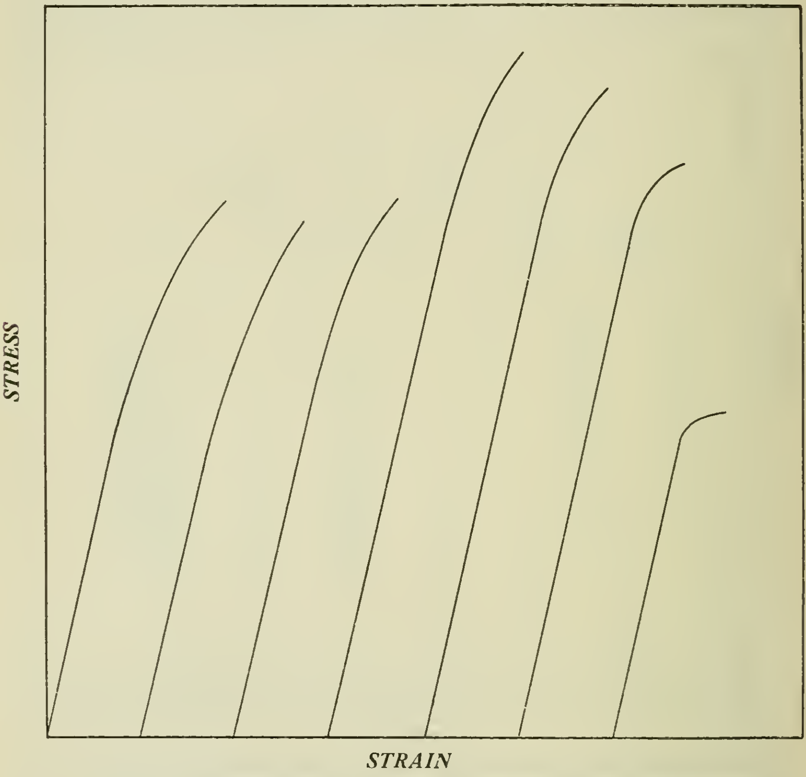

Fig. 4.—Series of load/extension curves taken from cold-worked steel as worked, and after blueing at temperatures from 100° to 600° C.

Determinations of the value of the limit of proportionality under compressile stresses have been carried out only on two steels—the air-hardening steel bar A and the cold-worked steel bar D. The air-hardening nickel-chromium steel bar was, however, tested in two sizes of specimen, 0·564 inch and 0·376 inch diameter. Strip steels are not suited to the preparation of specimens for compression tests. The results of the tests on these two steels are given in Tables XII., XIII., and XIV. As before, the duplicate test results are shown.

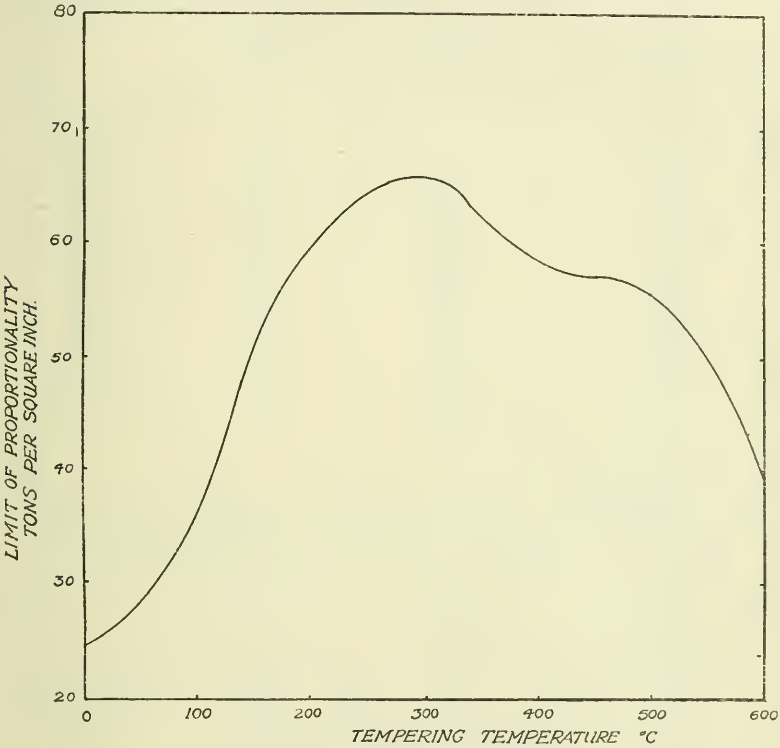

Fig. 5.—Curve showing the alteration in the limit of proportionality of air-hardened steel produced by tempering at different temperatures.

A selection of typical load/compression diagrams are shown for these two steels in Figs. 7 and 8, whilst in Figs. 9 and 10 are shown the general relationship between the compressile limit of proportionality and the reheating temperature to which the steel has been exposed.

The values of the limit of proportionality obtained on the steels when tested in compression are quite different from those obtained on the same steels when tested in tension. Speaking generally, the compressile limit of proportionality in the fully hardened steels is not really low—*i.e.*, not very much lower than the maximum value that can be obtained from such steel by reheating it to the temperature which produces in it the maximum value of the *tensile* limit of proportionality. Reheating to moderate temperatures does raise the compressile limit of proportionality, but only slightly. This difference in behaviour of the steels when tested in tension and in compression is noteworthy.

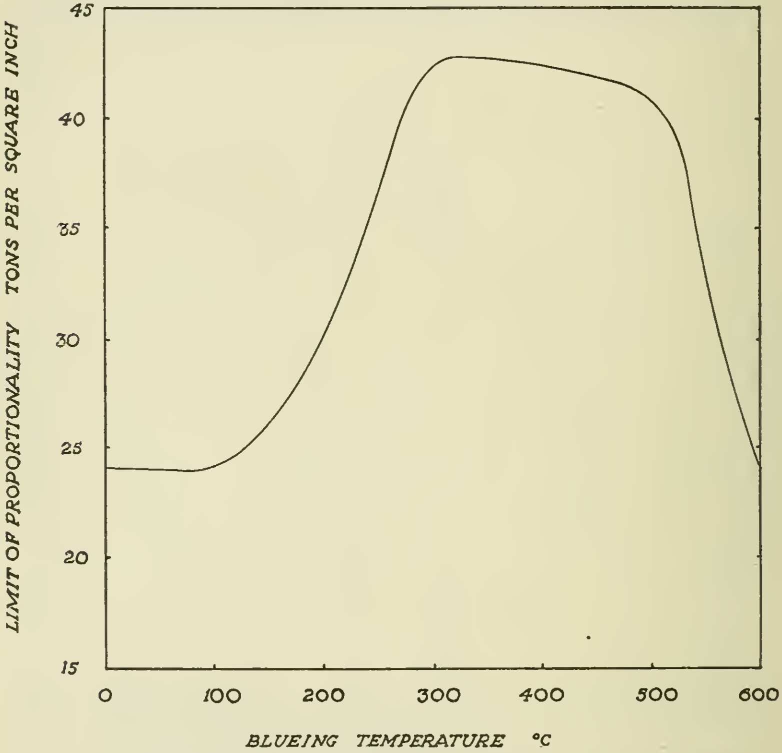

Fig. 6.—Curve showing the alteration in the limit of proportionality of work-hardened steel produced by reheating to different temperatures.

The next thing to observe in the investigation is the effect, if any, which the existence of a low limit of proportionality in a steel exerts upon the proof stress of the material. The definition taken of the proof stress is that given in the British Engineering

TABLE XII.—*The Limit of Proportionality in Compression of Air-hardening Nickel-Chromium Steel Bar A before and after Tempering at Different Temperatures* (0·564-*inch specimens*).

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
ACA1	830	...	64·1
ACA2	830	...	63·2
ACA3	830	100	71·0
ACA4	830	100	72·1
ACA5	830	200	76·2
ACA6	830	200	77·7
ACA7	830	300	73·1
ACA8	830	300	71·6
ACA9	830	400	63·3
ACA10	830	400	62·1
ACA11	830	500	51·4
ACA12	830	500	53·3
ACA13	830	600	39·8
ACA14	830	600	38·5

TABLE XIII.—*The Limit of Proportionality in Compression of Air-hardened Nickel-Chromium Steel Bar A before and after Tempering at Different Temperatures* (0·376-*inch specimen*).

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
ACB1	830	...	65·2
ACB2	830	...	67·1
ACB3	830	100	73·5
ACB4	830	100	70·2
ACB5	830	200	75·0
ACB6	830	200	77·1
ACB7	830	300	68·4
ACB8	830	300	65·8
ACB9	830	400	59·2
ACB10	830	400	58·2
ACB11	830	500	52·1
ACB12	830	500	54·3
ACB13	830	600	37·8
ACB14	830	600	38·2

Standards Association's Specifications for Strip Steel for Aircraft, which is of the stress which after application to the steel for fifteen seconds and removal results in the permanent distortion of the stressed steel by an elongation of 0·1 per cent. As the proof stress is a property which is regarded as being of considerable importance in engineering calculations, it is very necessary to determine whether or not a steel with a low limit of proportionality has a low proof stress value. (The proof stress is an attempt to give a definite usable value to the yield point, and as it represents something that is definite and also measurable, may be taken in place of the elastic limit or the yield point, whichever is the property utilised, being as definite as the former and as measurable as the latter.)

Table XIV.—*The Limit of Proportionality in Compression of Cold-worked Steel Bar D before and after Blueing at Different Temperatures.*

Mark.	Reheating Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.
DCA1	...	39
DCA2	...	39
DCA3	100	39
DCA4	100	41
DCA5	200	41
DCA6	200	43
DCA7	300	46
DCA8	300	46
DCA9	400	45
DCA10	400	44
DCA11	500	26·5
DCA12	500	26·0
DCA13	600	25·0
DCA14	600	25·0

The determination of the proof stress may be made by the direct measurement of the test specimen—that is, by the application and removal of successive increments of load and the measurement of the permanent distortion produced by these successive increments of load, until the stress value is attained which produces the necessary permanent elongation of 0·1 per cent. Alternatively it may be abstracted directly from the load/extension diagram. To do this it is necessary to assume that the amount of *elastic* strain produced in a steel is always proportional to the applied stress. That this is true is always assumed for stresses below the limit of proportionality (by definition), but it is currently assumed also to hold for stresses greater than the stress at the limit of proportionality. When such a greater stress is applied to the steel, the strain is compounded of elastic and plastic. It is desired to measure the latter strain. Actually a load/extension diagram indicates the total strain at any stress. If, however, the elastic strain can be assumed to be fixed by the stress and the normal value of the modulus of elasticity it is calculable for any stress, and the plastic strain obtained by the difference between the total and the elastic strain. This method is indicated

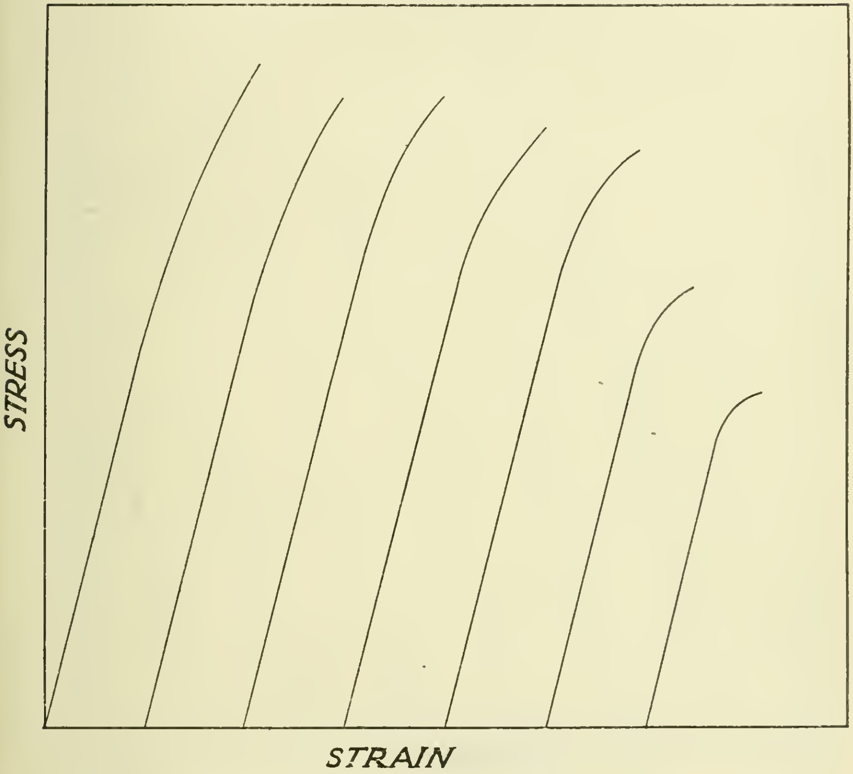

Fig. 7.—Series of load/compression curves taken from air-hardened steel bar as hardened and after reheating to temperatures from 100° to 600° C.

in Fig. 11, in which, at the stress P, the total strain is PX, the elastic strain PY, and the plastic strain XY. The line YZ is obviously the continuation of the line of proportionality, and is a hypothetical line. The degree of straightness with which this line is to be regarded as invested is a matter about which there may be a good deal of doubt (see results on p. 167).

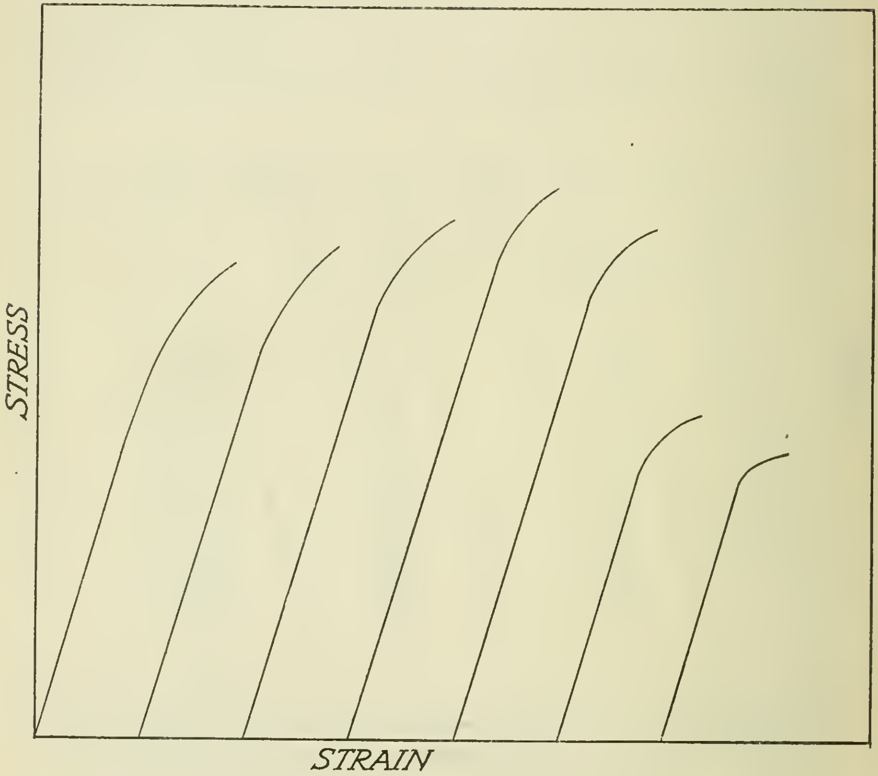

Fig. 8.—Series of load/compression curves of work-hardened bar before and after reheating to temperatures of 100° to 600° C.

Determination of the proof stress of the steels under discussion have been made by both the methods described above. The results obtained by the latter method will be reported first—*i.e.*, those taken directly from the load/extension diagram. In Tables XV. to XIX. appear the values of the proof stress obtained from the five different steel forms under investigation, both in

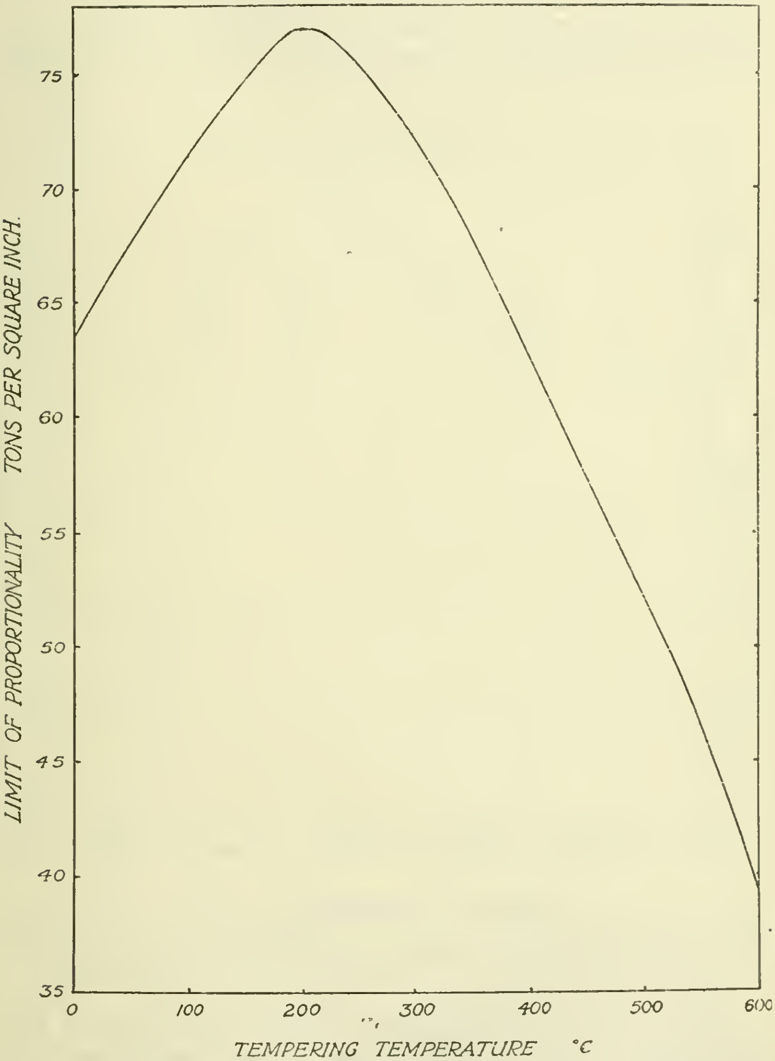

Fig. 9.—Curve showing the change of compressile limit of proportionality of air-hardened steel bar before and after tempering at temperatures of 100° to 600° C.

the fully hardened condition and after being reheated to different temperatures. In the curves shown in Figs. 12 and 13 are illustrated the values of the proof stress together with the values of the limit of proportionality and of maximum stress of the steels in these different conditions. These curves show very plainly the independent courses taken by these three properties.

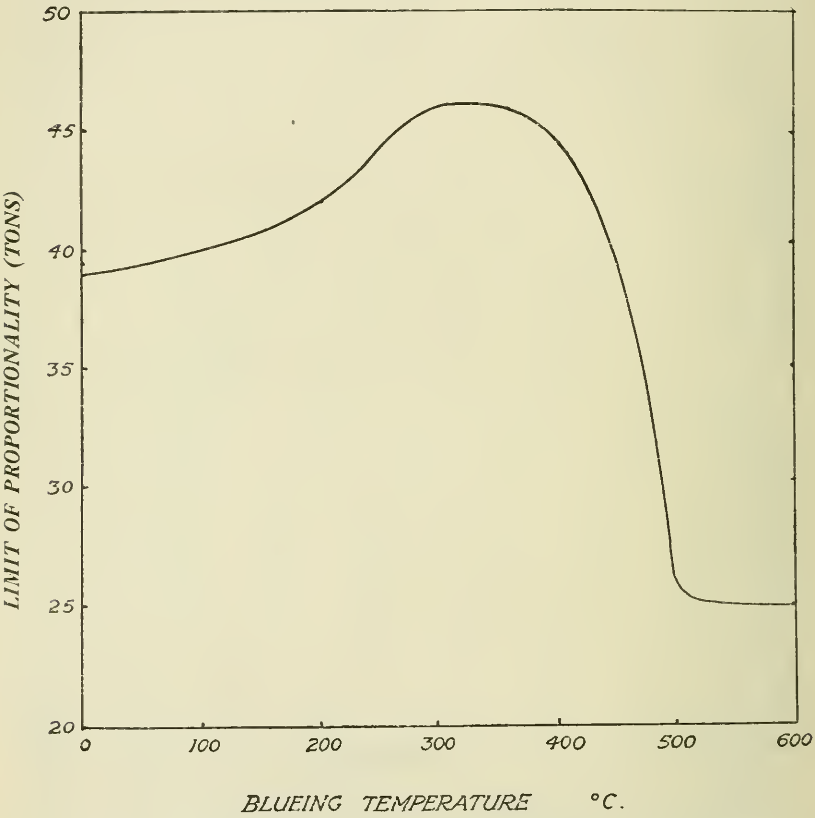

FIG. 10.—Curve showing the change in compressile limit of proportionality of work-hardened steel produced by reheating to various temperatures.

Before giving the results of the values for the limit of proportionality observed under various different conditions, it is convenient to report also the values obtained upon the compression test-pieces for the property corresponding to the tensile proof stress—*i.e.*, the stress which produces a compressile permanent distortion of 0·1 per cent. These are available only for the air-hardening bar steel A and the cold-worked steel bar D.

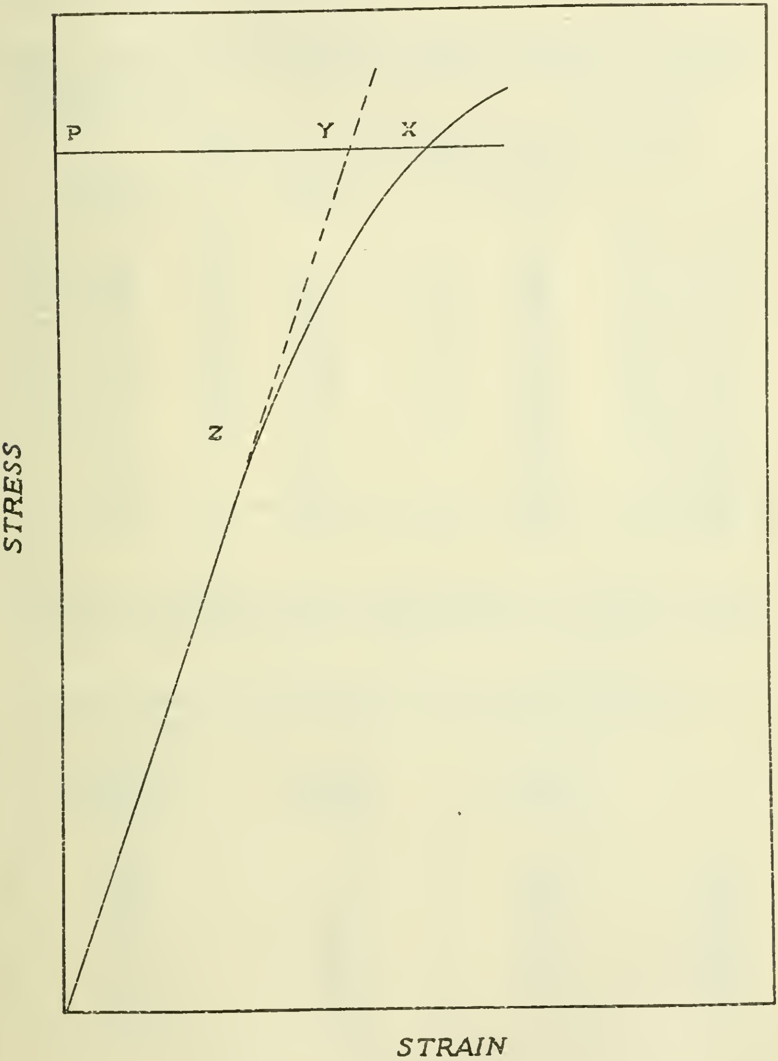

Fig. 11.

Here again the values have been extracted directly from the load/compression diagrams, and the results thus obtained are given in Tables XX. and XXI.

The test results show that the proof stress, like the limit of proportionality, in the fully quench-hardened steels and those lightly tempered is considerably higher in compression than in tension, but that after the steels have been tempered at temperatures which produce the optimum value of the limit of proportionality, there is little difference between the tension and compression values for the proof stress. There is not so much difference between the proof stress value in tension and in com-

TABLE XV.—*The Proof Stress in Tension of Air-hardened Nickel-Chromium Steel Bar A before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Proof Stress. Tons per Sq. In.
ATC1	830	...	66·5
ATC2	830	...	64·5
ATC3	830	100	68·6
ATC4	830	100	70·1
ATC5	830	200	82·5
ATC6	830	200	80·2
ATC7	830	300	78·6
ATC8	830	300	79·8
ATC9	830	400	74·2
ATC10	830	400	72·4
ATC11	830	500	65·1
ATC12	830	500	65·4
ATC13	830	600	48·1
ATC14	830	600	47·8

TABLE XVI.—*The Proof Stress in Tension of Air-hardened Nickel-Chromium Steel Strip B before and after Tempering.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Proof Stress. Tons per Sq. In.
BTC1	830	...	53·0
BTC2	830	...	57·8
BTC3	830	200	76·7
BTC4	830	200	77·6
BTC5	830	400	72·4
BTC6	830	400	71·0
BTC7	830	600	47·1
BTC8	830	600	51·4

pression on the work-hardened steel—the value in compression being slightly higher, nevertheless.

TABLE XVII.—*The Proof Stress in Tension of Oil-hardened Nickel-Chromium Steel Bar C before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Proof Stress. Tons per Sq. In.
CTC1	830	...	68·1
CTC2	830	...	67·2
CTC3	830	100	77·1
CTC4	830	100	77·3
CTC5	830	200	86·9
CTC6	830	200	86·1
CTC7	830	300	82·1
CTC8	830	300	81·8
CTC9	830	400	76·9
CTC10	830	400	77·0

In view of the very marked difference between the values recorded for the limit of proportionality and the proof stress of the fully hardened steel, some careful tests were made to find whether the departure from proportionality shown by the extensometer curves did really indicate that the steel was undergoing

TABLE XVIII.—*The Proof Stress in Tension of Cold-worked Steel Bar D before and after Blueing.*

Mark.	Reheating Temperature. ° C.	Proof Stress. Tons per Sq. In.
DTC1	...	40·2
DTC2	...	40·8
DTC3	100	41·5
DTC4	100	40·6
DTC5	200	45·4
DTC6	200	42·8
DTC7	300	54·4
DTC8	300	53·7
DTC9	400	52·0
DTC10	400	51·7
DTC11	500	45·2
DTC12	500	45·2
DTC13	600	26·0
DTC14	600	24·8

a measure of plastic and permanent distortion, or whether the steel was still really disproportionately elastic at stresses higher than the limit of proportionality. The latter behaviour would certainly be unusual, but not really impossible. The test was made by loading the steel to a definite value, and removing the load at intervals and allowing the steel full opportunity to resume its natural dimensions. The permanent deformation if any was then noted. It was found in general that the lowest stress at which the steel showed that it had taken up a permanent deformation was substantially the same as that at which the extensometer curve showed a departure from the proportional range. In other words, these tests showed that the load/extension curves did really indicate the behaviour of the material, and that the steel when exposed to a stress slightly higher than the limit of proportionality received a definite small amount of permanent deformation.

TABLE XIX.—*The Proof Stress in Tension of Cold-worked Strip E before and after Blueing.*

Mark.	Reheating Temperature. ° C.	Proof Stress. Tons per Sq. In.
ETC1	...	62·8
ETC2	...	61·6
ETC3	100	60·3
ETC4	100	60·1
ETC5	200	59·8
ETC6	200	58·6
ETC8	300	61·9
ETC10	400	62·9
ETC11	500	51·6
ETC12	500	53·4
ETC13	600	27·2
ETC14	600	31·6

The specimens tested were taken from the air-hardening steel strip B. The steel was tested after hardening in the air from 830° C., and after reheating to 200°, 400°, 600° C., respectively. The results of the determinations are shown in Table XXII.

Similar tests were made upon the cold-worked steel strip E. In this case only two sets of specimens were examined, namely, one as fully worked and the other after blueing at a temperature of 400° C. In this steel too the results were quite definite in showing that a stress slightly superior to the limit of proportionality shown by the load/extension curves produced a definite permanent deformation of the steel. For this steel the results are as shown most clearly in the curves in Fig. 14 The curves

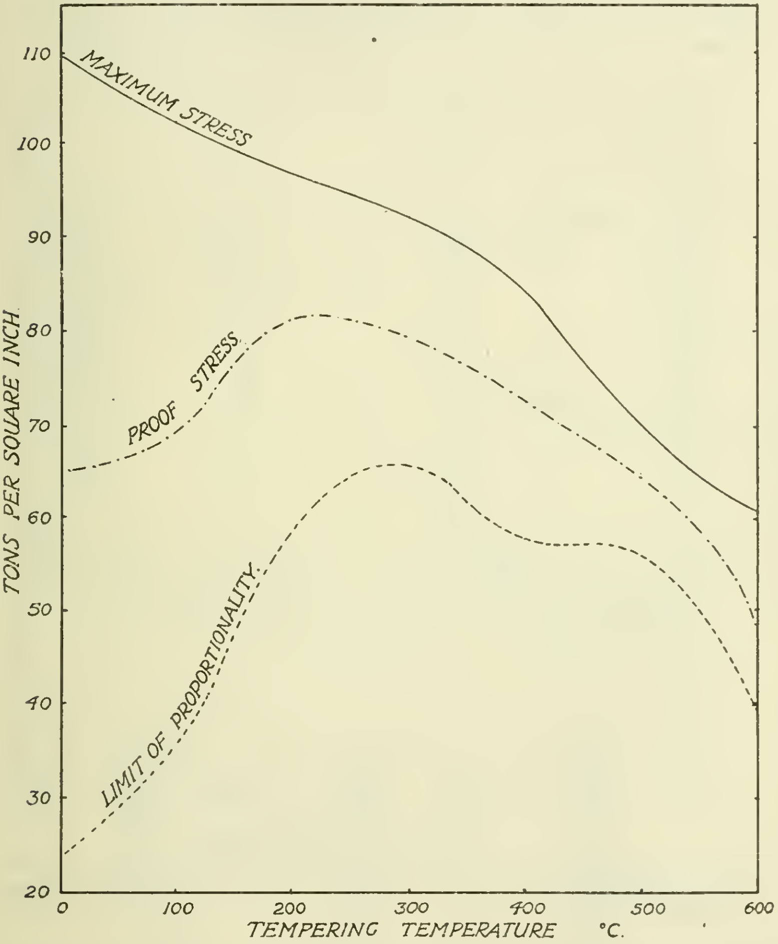

Fig. 12.—Curves showing the changes in maximum stress, proof stress, and limit of proportionality of air-hardening steel bar produced by tempering at different temperatures.

shown indicate, first of all, the ordinary load/extension curves for the steel in the two conditions tested, and the accompanying curve of the permanent deformation produced at the different stress values. Clearly the departure from proportionality indicates the permanent deformation of the test specimen.

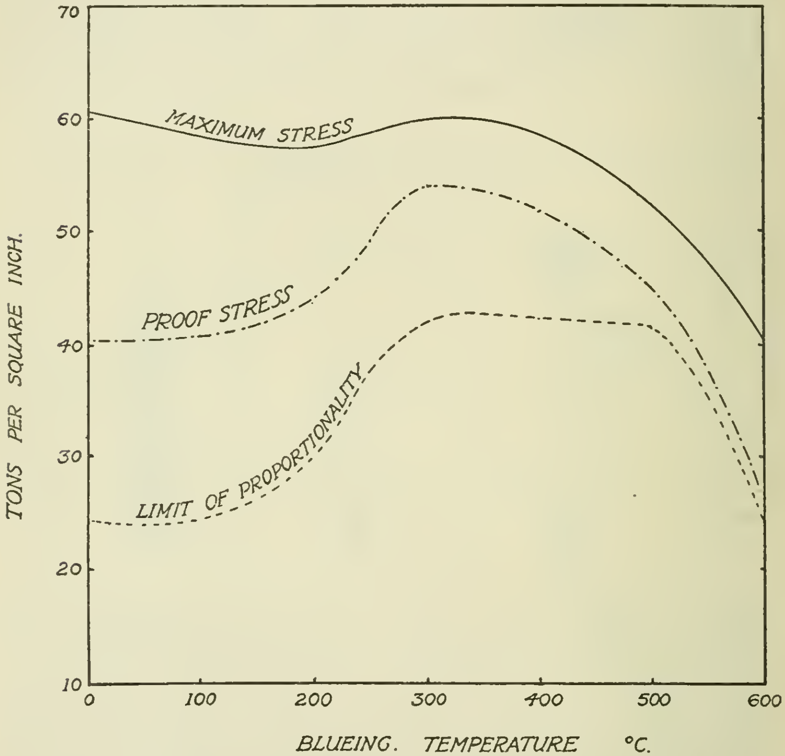

FIG. 13.—Curves showing the changes in maximum stress, proof stress, and limit of proportionality of cold-worked steel bar produced by reheating to various temperatures.

In connection with these tests it is important to note the other results obtained on the work-hardened metal after exposure to fatigue stresses and reported below.

The effect of reheating the air-hardening steel to various temperatures is to raise the value of the limit of proportionality. The maximum value that is attained by the limit of proportionality is produced at a tempering temperature which varies with the particular steel that is being treated. It is generally, however, at a tempering temperature round about 400° C. that the optimum value is attained. This statement refers to the effect of quite brief exposures—*i.e.*, such as would be given in commerce

Table XX.—*The Proof Stress in Compression of Air-hardened Nickel-Chromium Steel Bar A before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Proof Stress. Tons per Sq. In.
ACC1	830	...	97·5
ACC2	830	...	100·2
ACC3	830	100	94·1
ACC4	830	100	93·8
ACC5	830	200	93·7
ACC6	830	200	93·5
ACC7	830	300	78·2
ACC8	830	300	79·1
ACC9	830	400	78·3
ACC10	830	400	75·7
ACC11	830	500	59·8
ACC12	830	500	60·4
ACC13	830	600	44·5
ACC14	830	600	46·3

Table XXI.—*The Proof Stress in Compression of Cold-worked Steel Bar D before and after Blueing at Different Temperatures.*

Mark.	Reheating Temperature. ° C.	Proof Stress. Tons per Sq. In.
DCC1	...	42·5
DCC2	...	42·8
DCC3	100	44·6
DCC4	100	43·6
DCC5	200	46·0
DCC6	200	46·7
DCC7	300	51·7
DCC8	300	52·1
DCC9	400	48·0
DCC10	400	48·0
DCC11	500	27·5
DCC12	500	27·5
DCC13	600	28·1
DCC14	600	27·9

—to the effect of the temperature. Some tests, however, have been made to ascertain the effect of a prolonged exposure to low temperatures in order to ascertain whether the limit of proportionality is disproportionately affected by this treatment. Two specimens of steel B were tempered at 100° C. for a long time after having been hardened in the air from 830° C. The limit of proportionality of the specimens was then determined, and also the stress value which produced a definite and measurable amount of permanent distortion. One specimen was heated at 100° C. for two days, and the other for seven days. The results of the tests are shown in Table XXIII.

TABLE XXII.

Mark.	Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.	Stress at which a Permanent Extension was Measurable.
BT31	830	...	23·5	26·5
BT32	830	...	25·2	28·0
BT33	830	200	56·5	58·0
BT34	830	200	53·5	56·5
BT35	830	400	65·0	67·0
BT36	830	400	63·5	66·0
BT37	830	600	43·5	45·5
BT38	830	600	45·5	47·0

TABLE XXIII.—*The Effect of Prolonged Tempering at a Low Temperature upon the Limit of Proportionality of an Air-hardened Nickel-Chromium Steel (B).*

Mark.	Tempering Temperature. ° C.	Tempering Time.	Limit of Proportionality. Tons per Sq. In.	Stress at which Measurable Permanent Extension is Produced. Tons per Sq. In.
BT40	100	2 days	52·0	55·0
BT41	100	7 ,,	53·0	56·5

Clearly the exposure for long periods at low temperatures brings about a change in the metal that is commensurate with a shorter exposure at higher temperatures, and the higher limit of

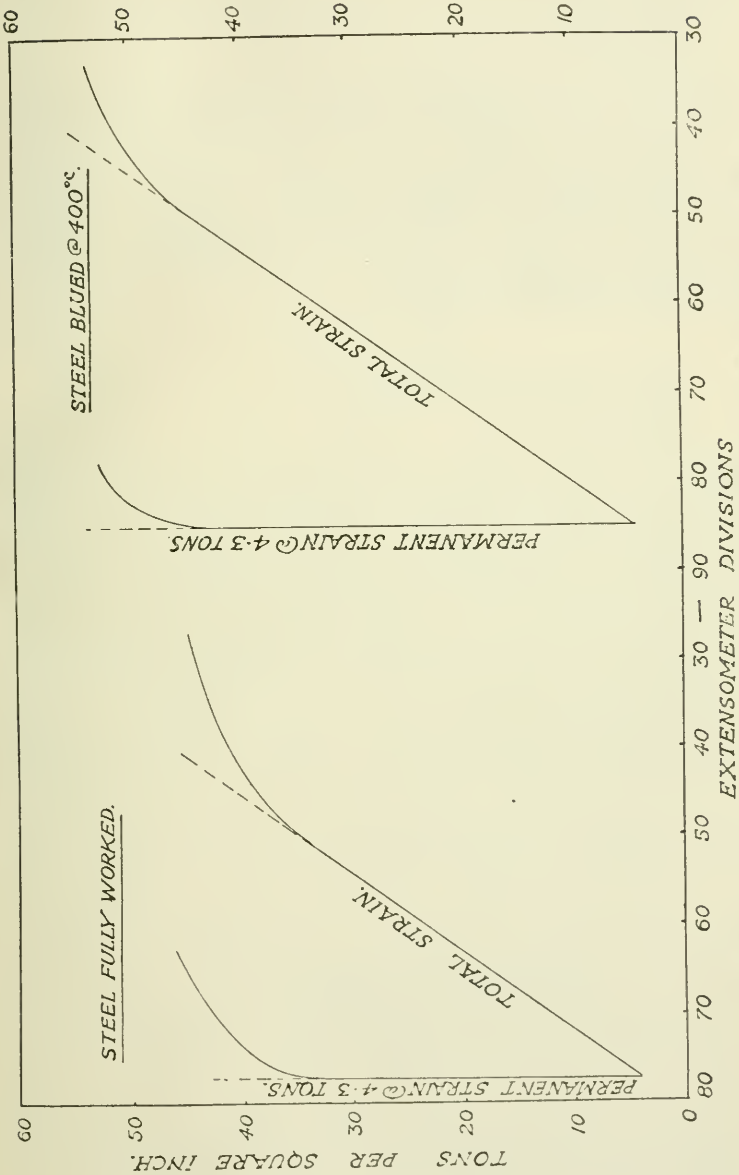

FIG. 14.—Curves showing permanent distortion of cold-worked steel at the proof stress.

proportionality thus produced is an indication that a definite and measurable permanent deformation is produced when the stress is exceeded.

The effect of reheating the air-hardening steel strip B to a low temperature for a prolonged period is to raise the limit of proportionality very markedly to a value approximately equal to that produced by exposure to the optimum tempering temperature. The effect of a similar treatment applied to the cold-worked steel strip E has therefore been investigated. The steel was heated at 100° C. for seven days and then tested. The result of the test was as follows :

Specimen ET20.

Limit of proportionality, tons per sq. in. . . .	30·1
Proof stress ,, ,, . . .	55·4

The value of the limit of proportionality in this steel as fully hardened is about 23·5 tons per square inch. The optimum value attained by it on blueing is 45 tons per square inch, which is produced by reheating the steel to a temperature of 300° C. Clearly, therefore, the prolonged heating at 100° C. of the work-hardened steel has had a comparatively small effect upon the value of the limit of proportionality as compared with that upon the same property of the alloy steel when air hardened.

Having determined the effect of a prolonged time of heating upon the limit of proportionality, experiments have been made to determine the effect upon the steel of a prolonged application of stress. It would appear probable that if the low limit of proportionality were attributable to the simple release of strains in the metal, the prolonged application to it of a load at the value at which the load/extension curve departs from proportionality—*i.e.*, the stress at which by this theory the strains are relieved—would relieve these strains and thereby enable the metal to behave as though it were truly elastic at stresses much higher than those indicated by the limit of proportionality. A test has, therefore, been made by (i) loading the steel until the load/extension curve indicated a departure from proportionality, (ii) maintaining the stress on the metal until no further extension occurred—*i.e.*, until the creep was complete, (iii) raising the load slightly, (iv) allowing the creep once again to become complete, and (v) repeating the loading and creeping at successively higher stresses. The result of the test is shown in Fig. 15. The load/extension

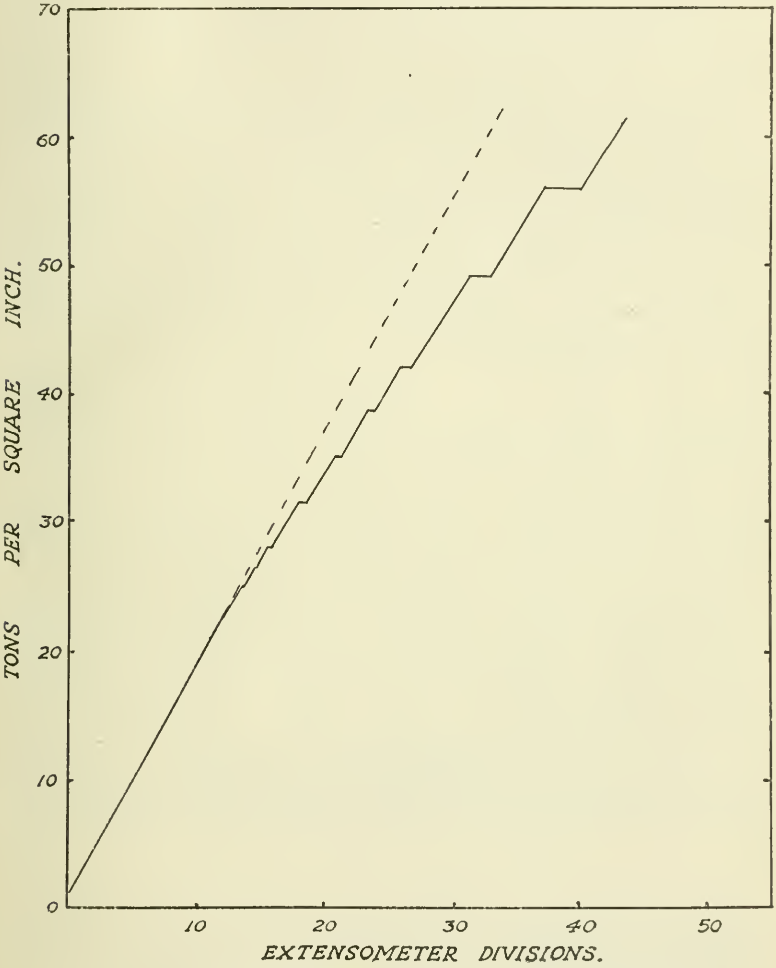

Fig. 15.—Curve showing creep at different loads during prolonged test of air-hardened steel strip.

curve shows that the prolonged application of a low stress has by no means produced the result suggested. As the load is increased the deformation is progressively increased, so that the load/extension curve shown is really only a stepped variety of the ordinary curve. The value for the limit of proportionality is of course normal—*i.e.*, 25·5 tons per square inch, whilst the value of the proof stress as obtained in this way—*i.e.*, 60 tons per square inch—is also substantially that given by the ordinary load/extension curve.

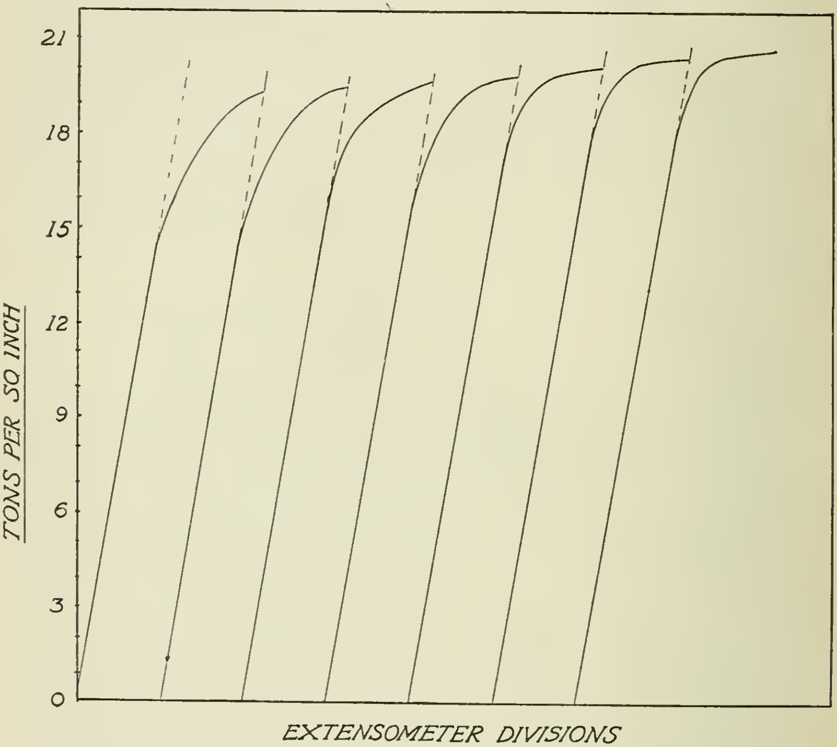

Fig. 16.—Series of load/extension curves on normalised steel, the steel being stressed up to its proof stress each time.

A somewhat similar test is provided by an investigation of the effect upon the limit of proportionality of successively loading the steel to a stress value equal to the proof stress. With normal material the effect of loading a steel to a stress that is markedly higher than its limit of proportionality is to strain it appreciably, and when the strained material is again tested, it shows a load/extension curve that is a straight line nearly up to the highest stress value previously applied, the steel being completely elastic up to this point (see Fig. 16). In the majority of steels the limit of proportionality is but a few tons per square inch lower than the yield point (if one exists), and in most steels but a few tons below the stress at which the load/extension curve falls away very markedly. As a result, if the steel is stressed to a load that produces a plastic deformation, the yield point (or its commercial equivalent) is reached. On retesting such a steel the load/extension curve is straight (elastic) almost up to the value of the previously applied stress, but thereafter falls off very sharply and abruptly—indicating the production of a large strain at stresses only slightly above the new and induced limit of proportionality. The behaviour of such a steel is shown in the test results given in Table XXVII.

With the strip steel B, tests have been made by taking a load/extension curve up to the proof stress of the metal, removing the stress altogether, and giving the steel time to recover, and then taking another load/extension curve to the new proof stress of the metal. This has been repeated no less than five times on the test-piece, the limit of proportionality and the proof stress being noted at each time of loading. The result is that even when the loading has gone to a very high figure, the value of the limit of proportionality and the proof stress (or the yield point) never coincide. The actual observations are shown in Table XXIV. The specimen was originally hardened in the air from 830° C. At each stage of the test the load was removed when it had attained the proof stress value, and the specimen rested.

TABLE XXIV.

History of Test-Piece.	Limit of Proportionality. Tons per Sq. In.	Proof Stress. Tons per Sq. In.
Air-hardened, not heated, tested to proof stress .	12·6	46·5
Rested and tested to new proof stress . .	46·2	61·4
Rested and tested to 3rd ,, ...	61·6	74·5
Rested and tested to 4th ,, ...	74·1	83·2
Rested and tested to 5th ,, ...	82·2	89·9

The total plastic extension of the test-piece was only 0·5 per cent. of the gauge length of the specimen. The test shows that even when the limit of proportionality of the steel was thus artificially raised to a value that is nearly seven times as great as it is originally, the value of the limit of proportionality still had not overtaken even the proof stress. The behaviour of this specimen suggests that the steel is undergoing a continuous change by the application of the different loads, and is not at once definitely overloaded in the way that a plain carbon steel would be.

TABLE XXV.—*Cold-worked Steel Strip E.*

History of Test-Piece.	Limit of Proportionality. Tons per Sq. In.	Proof Stress. Tons per Sq. In.
Cold worked, loaded to proof stress . . .	24·5	52·9
Load removed, and specimen reloaded to new proof stress	48·0	57·0
Load removed, and specimen reloaded to third proof stress	49·6	58·7

TABLE XXVI.—*Cold-worked Steel Strip E.*

History of Test-Piece.	Limit of Proportionality. Tons per Sq. In.	Proof Stress. Tons per Sq. In.
Cold worked, loaded to proof stress . . .	25·2	54·6
Load removed, and specimen reloaded to new proof stress	51·0	59·8
Load removed, and specimen reloaded to third proof stress	55·0	61·9

Similar tests have been made upon the cold-worked steel strip E. As with the alloy steel strip, the specimen was stressed to the value of the proof stress and the load removed. The specimen was then again stressed and the value of the limit of proportionality noted ; the stressing proceeding to the value of the new proof stress, and so on. The values obtained in the two tests made are given in Tables XXV. and XXVI., and show very clearly the kind of result that is obtained in such a test. As with the air-hardening steel A, the value of the limit of proportionality on the second stressing is raised to a value that is approximately equal to the proof stress on the first loading, whilst the third limit of proportionality is approximately equal to the second proof stress.

The results of the tests shown in Tables XXV. and XXVI. are quite definitely different from those obtained on a normalised plain carbon steel such as are shown in Table XXVII.

TABLE XXVII.—*Normalised Plain Carbon Steel.*

History of Specimen.	Limit of Proportionality. Tons per Sq. In.	Proof Stress. Tons per Sq. In.
Loaded to 1st proof stress . .	14·45	19·4
,, 2nd ,, . .	14·45	19·6
,, 3rd ,, . .	15·75	19·8
,, 4th ,, . .	15·75	19·9
,, 5th ,, . .	17·4	20·2
,, 6th ,, . .	17·85	20·4
,, 7th ,, . .	17·85	20·6

In addition to the tests made upon the nickel-chromium steels in the air-hardened state some were made upon the alloy steel bar A after quenching in water. The experiments were made upon two sizes of specimen, that were machined approximately to size before heat treatment. The sizes were (in the gauge length) respectively 0·564 inch and 0·376 inch diameter. A set of specimens in each size were subjected to test in the following conditions :

1. Hardened in water from 830° C.
2. Hardened in water from 830° C. and tempered at 400° C.
3. Hardened in air from 830° C.
4. Hardened in air from 830° C. and tempered at 400° C.

The results of the tests were fairly conclusive and were the same in both sizes of specimen. The general result was that the limit of proportionality was not affected appreciably by the method of hardening—*i.e.*, that the value of this property in the specimens cooled in air was not noticeably different from the value in the specimen cooled in water. In the specimens tempered at 400° C. in each size, and after hardening in either air or water, the value of the limit of proportionality was substantially the same.

During the hardening of a piece of steel it is almost certain that the outside will always cool rather more rapidly than the interior. It is also likely that the outer layers will be rather less constrained than the interior and will be able to take up their normal volume more nearly than the metal in the interior of the piece—which will be naturally rather less free and also will suffer from the temperature hysteresis between the exterior and the interior. The effect of the temperature hysteresis in a bar of steel is to permit the transformation of austenite to martensite to occur, in so far as it ordinarily will, on the outside of the bar before it occurs in the interior, and hence to produce some greater rigidity in the outer layers. When the interior of the specimen reaches the critical temperature or range and attempts to expand into martensite, the superior rigidity of the exterior layers will tend to hinder this expanison, and will therefore tend to retain in the interior a somewhat larger proportion of austenite. When the outside of the steel is removed by grinding, the source of some of the pressure on the interior is also taken away, and the interior part is more free to expand in accordance with its desire and therefore to pass from the austenitic to the martensitic state. In any event a certain amount of the strain in the austenite is relieved by this treatment. If, therefore, the existence of austenite has any influence, mediate or immediate, upon the value of the limit of proportionality, there should be signs of a difference in the value when a large or a small piece of steel is tested.

An experiment has, therefore, been made by taking several specimens of a 1-inch round bar of the air-hardening steel A and hardening them from a temperature of 830° C. in the air and then grinding them down—cold and wet and slowly—to a smaller diameter, and testing in that size. Two sizes of test-piece were produced in this way, having diameters respectively of 0·564 inch and 0·376 inch. The value of the limit of proportionality on those two samples on testing were respectively :

Diameter.	Limit of Proportionality. Tons per Sq. In.
0·376 inch	56
0·564 „	46

In each test-piece the removal of the exterior had resulted in a very marked increase in the value of the limit of proportionality as compared with that in a specimen that had not been machined appreciably before testing. Also the one that had been machined the most—*i.e.*, the test-piece with the smaller diameter—had the higher value of limit of proportionality, corresponding with what was assumed as to the progressively greater relief of pressure between the austenite and martensite of the core of the specimen. (It is interesting in this connection to refer to the fact that a long bar of steel that is hardened gradually increases in length if the exterior of the bar is gradually removed by machining. The two effects dealt with are clearly the same.)

It may be noted here that no such effect is produced with the work-hardened steel. Specimens were tested without machining and also after machining down to ordinary sizes, but the value of the limit of proportionality was substantially the same in all cases. Also, no apparent change of dimensions in the bar is brought about by machining away the skin of the metal.

The influence of the low limit of proportionality upon the fatigue strength of the steels has been investigated directly. The fatigue tests have been made by the Wöhler method with a solid specimen. Upon the air-hardening steel bar, A, tests were made in the fully air-hardened condition and after tempering at a temperature of 400° C. If these tests had shown anything very unusual it was intended to test specimens that had been tempered at other and different temperatures. The actual test values obtained are given in Table XXVIII.

Table XXVIII.—*Fatigue Tests on Air-hardened Nickel-Chromium Steel Bar A.*

Hardening Temperature. ° C.	Tempering Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.	Maximum Stress. Tons per Sq. In.	Fatigue Range. Tons per Sq. In.
830	...	24·3	112	±46·5
830	400	58·2	85	±41·0

The ratio of fatigue range to maximum stress for the fully air-hardening steel is 0·84 and for the steel tempered at 400° C.

is 0·96. The ratio for the tempered steel is therefore considerably superior to that for the fully hardened steel. The values would appear to show that the existence of the low value of limit of proportionality is not without its effect upon the fatigue properties of the steel. Nevertheless the fatigue range is not seriously lowered. The results appear to be in accordance with others obtained upon steel of this type. There appeared to be no necessity to investigate the actual values in fatigue of specimens tempered at other temperatures.

The cold-worked steel bar D has been tested in two conditions—one as fully cold worked, and the other after blueing at a temperature of 400° C. (that raises the limit of proportionality to its maximum value). The tests on this steel were made in the same way as on the alloy steel A. The actual results obtained are given in Table XXIX.

TABLE XXIX.—*Fatigue Tests on Cold-worked Steel Bar D.*

Reheating Temperature. ° C.	Limit of Proportionality. Tons per Sq. In.	Maximum Stress. Tons per Sq. In.	Fatigue Range. Tons per Sq. In.
...	23·3	60·6	±24
400	42·2	58·4	±26

The ratio of fatigue range to maximum stress in the steel cold worked but not blued is as low as 0·79, whereas the corresponding ratio for the steel that has been blued is 0·89. The latter value is just about the same as that for a normalised plain carbon steel of this type, but the value for the cold-worked material is definitely lower. These tests indicate a distinct difference in fatigue value that accompanies the difference in limit of proportionality, and indicates that the low limit of proportionality in this steel, as in the quench-hardened steel, is accompanied by a low fatigue range.

One of the most important factors regarding the low value of the limit of proportionality is the practical effects that may follow from its existence. Naturally such effects are likely to be of considerable importance in respect of the behaviour of such materials when stressed in fatigue. It has already been indicated that the fatigue range of the quench-hardened steel does not appear to be entirely unaffected by the existence of the low limit of proportionality, whilst in the cold-worked steel the fatigue range is lower in the steel with the low limit of proportionality, though in each steel there is no kind of constant ratio between the limit of proportionality and the fatigue range. It seems necessary to examine more fully the behaviour of the steels when exposed to fatigue stresses, and this has been achieved through the very generous co-operation of Professor Haigh, of the Royal Naval College, Greenwich, and Mr. A. S. Robertson, who have made the experiments upon the Haigh fatigue-testing machine, and to whom all thanks are given.

The first series of tests was made upon the air-hardening nickel-chromium steel bar A after it had been hardened in the air from 830° C. The first test was to subject the material to a static test. This showed the limit of proportionality at 25·5 tons per square inch. The load after each increment of stress was reduced to 4 tons per square inch to determine whether permanent strain had been produced or not. It was found that a measurable inelastic strain was produced at the stress called the limit of proportionality. The loading was then continued to a value of 40·8 tons per square inch. The form of the load/extension curve is shown in Fig. 17, together with the record of the permanent strain at different loads. The specimen was then loaded and unloaded through a range of 42·6 tons per square inch between the limits of 4·2 and 46·8 tons per square inch several times, and the form of the hysteresis loop observed. The mean width of the loop decreased rapidly during the first few cycles, the ratio of the width of the first loop to the twentieth being 70 to 19, at which the area of the loop appeared to settle down fairly definitely.

The second specimen was first of all submitted to a fatigue test, or rather was exposed to fatigue stresses before it was tested statically. The specimen endured 316,000 cycles of the same range of stress as were given to the first specimen, *i.e.* from 4·2 to 46·8 tons per square inch. Observations were made of the hysteresis during the run, and it was found to become substantially constant. The specimen was then stressed statically with the results shown in Fig. 18, for load/extension and for permanent strain. The result of this test shows that the value of the limit of proportionality has been raised definitely to a value of 47·0 tons per square inch. The remaining properties of the steel were not affected. Observations of the hysteresis loops were made after the fatigue run, between the stress limits of 4·2 and 42·6 tons per square inch, and it was found that the mean width was 16·5 as compared with the 19 obtained in the first test after only twenty cycles. Evidently the endurance of 316,000 cycles

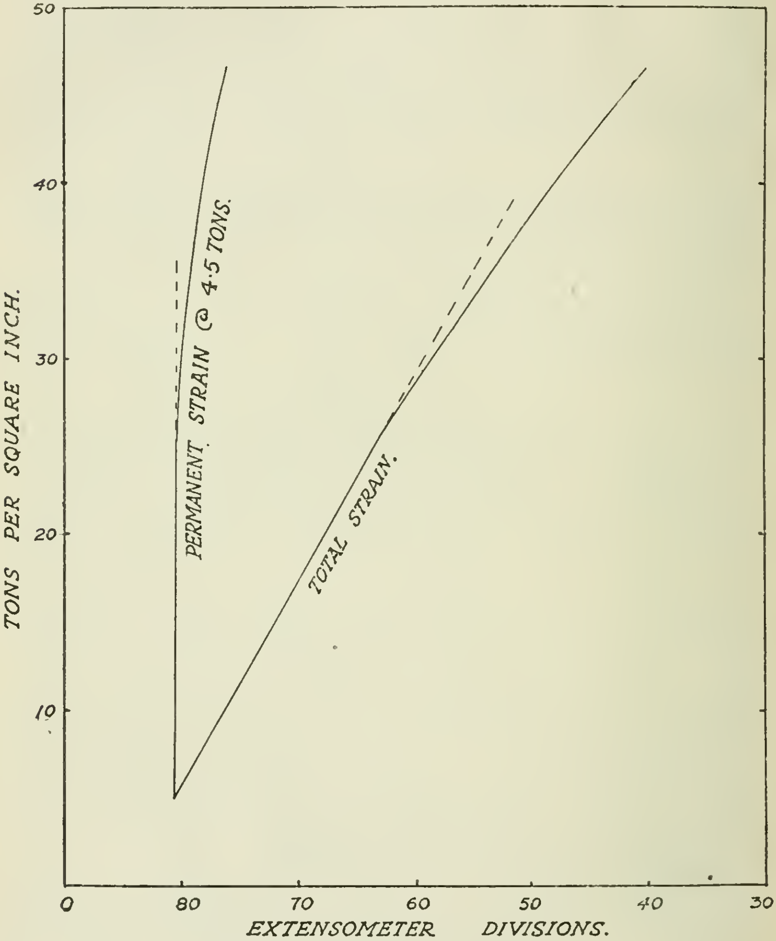

FIG. 17.—Air-hardening steel bar.

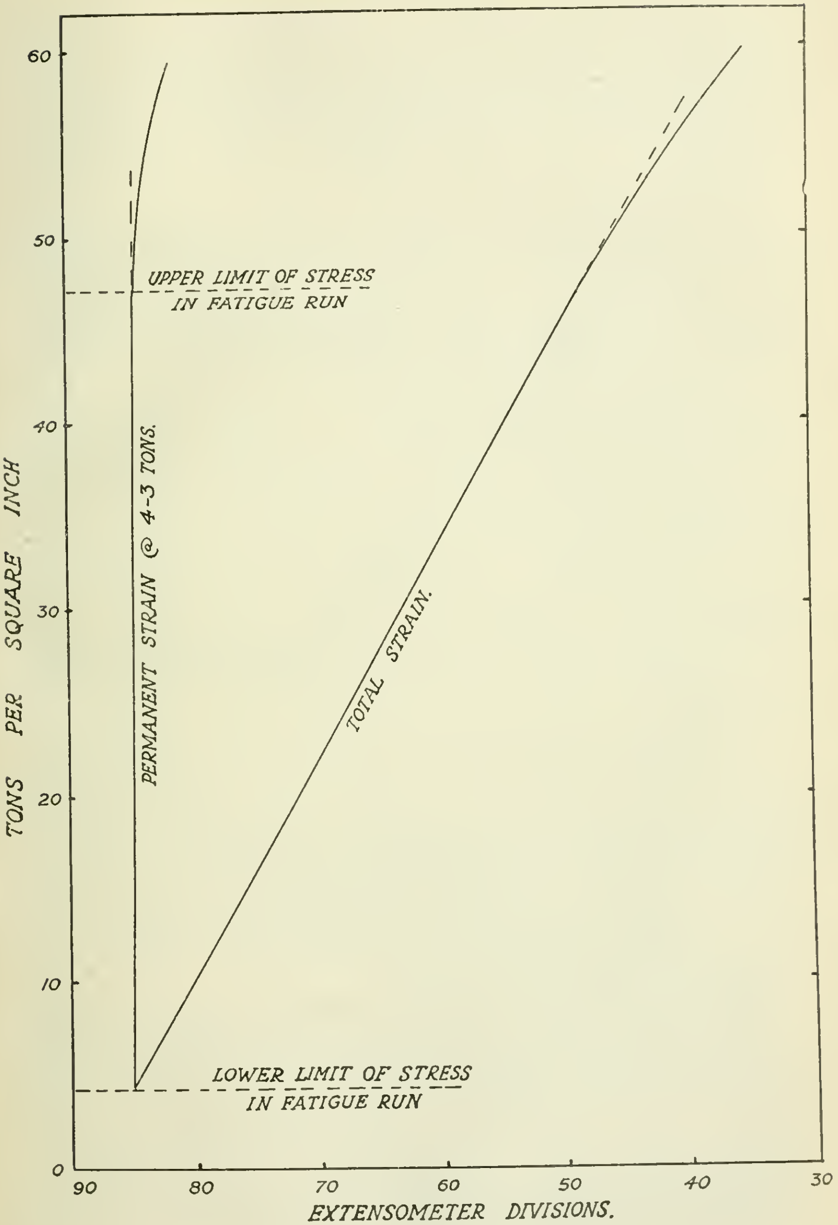

Fig. 18.—Air-hardening steel bar tested after fatigue stressing.

has not appreciably altered the hysteresis in the steel. An observation was also made of the hysteresis loop between 4·2 and 59·5 tons per square inch—*i.e.*, to an upper stress greater than the observed limit of proportionality. This gave a width of the hysteresis loop of 27—an increase in width that was to be expected.

The third specimen was exposed to only fatigue stresses and endured 300,000 cycles of a stress fluctuating between 4·2 and 58 tons per square inch. With this range of stress the hysteresis was markedly greater than in the second specimen, the ratio being 6·4 to 1 between the two specimens. Evidently the upper limit of stress is beyond the fatigue endurance limit.

The fourth specimen was treated in a manner similar to the third in that it was first subjected to a fatigue stress between 0 and 54 tons per square inch before being tested in static tension. The fatigue stress was endured for 100,000 cycles, and after this it was found that the limit of proportionality was as high as 54·5 tons per square inch. The values obtained for this specimen in the final static test are shown in Fig. 19. An observation of the hysteresis loop was made between the stress range of 4·2 to 46·8 tons per square inch (*i.e.*, as in tests 1 and 2), and the mean width of the loop was found to be brought down to 10 as compared with the 16·5, the lowest previously recorded.

In the fifth test the steel was submitted to a treatment very similar to that accorded to the third specimen. In this case the specimen was submitted to an endurance of 100,000 cycles under a stress range between 0 and 60·5 tons per square inch. After the fatigue stressing, the specimen was submitted to a static test, and the first permanent strain was found at 56·5 tons, there being a quite large inelastic strain at 66·5 tons per square inch. This test result is shown in Fig. 20.

During the whole of the fatigue tests observations were made of the evolution of heat that occurred in the specimen. This is a measure of the internal work that is being performed in the material due to the application of the fatigue stress, and consequently is some indication of any marked changes that are proceeding in the steel. These changes may be constitutional or may be merely physical. The observations made in this particular series of tests showed that there was very little heat evolution during the running of any of the specimens. This is in conformity with the hysteresis observations, and suggests that the steel is not undergoing a very marked change, either constitutional or physical. The alteration, therefore, that produces the superior values of the limit of proportionality after stressing in fatigue must be necessarily of a comparatively minute order—particularly in view of the fact that there is a great change in the area of the hysteresis loop in consequence of the application of only a small number of stress cycles.

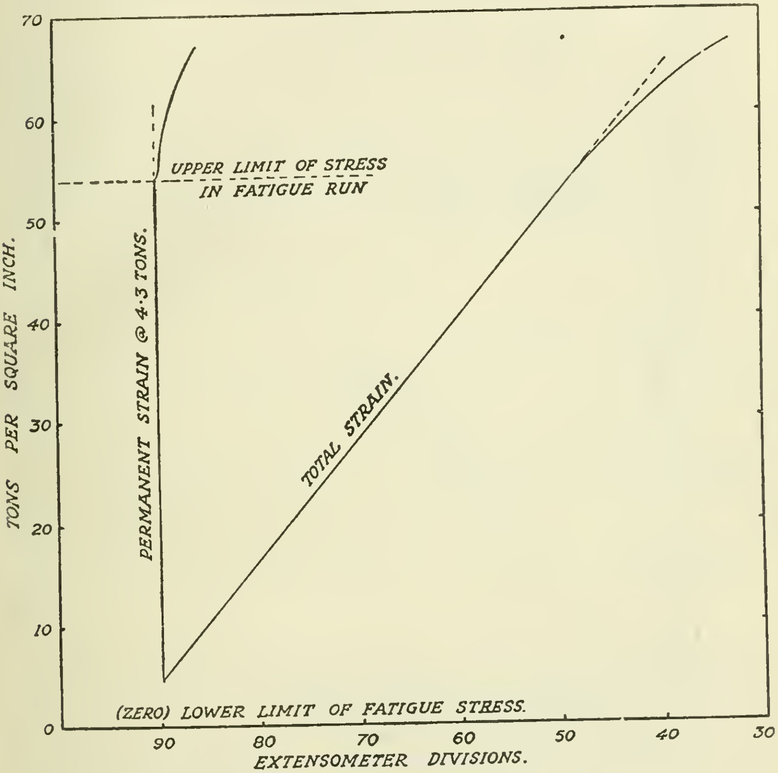

FIG. 19.—Air-hardening steel bar tested after fatigue stressing.

The effect of the application of the fatigue stresses to the specimens is to raise the value of the limit of proportionality in the steel very definitely. The new value of the limit of proportionality is always as high as the upper limit of fatigue stress that is applied to the steel, and in some cases is actually higher, though not very much higher. In none of the experiments was the limit of proportionality raised by fatigue stress to the optimum value attained in the steel by tempering at the optimum temperature. It is fair, therefore, to assume that the alteration produced by the applied fatigue stress is not necessarily the same as that produced by tempering. If the change is the same or similar in nature, it is not the same in degree. It is, however, very noteworthy

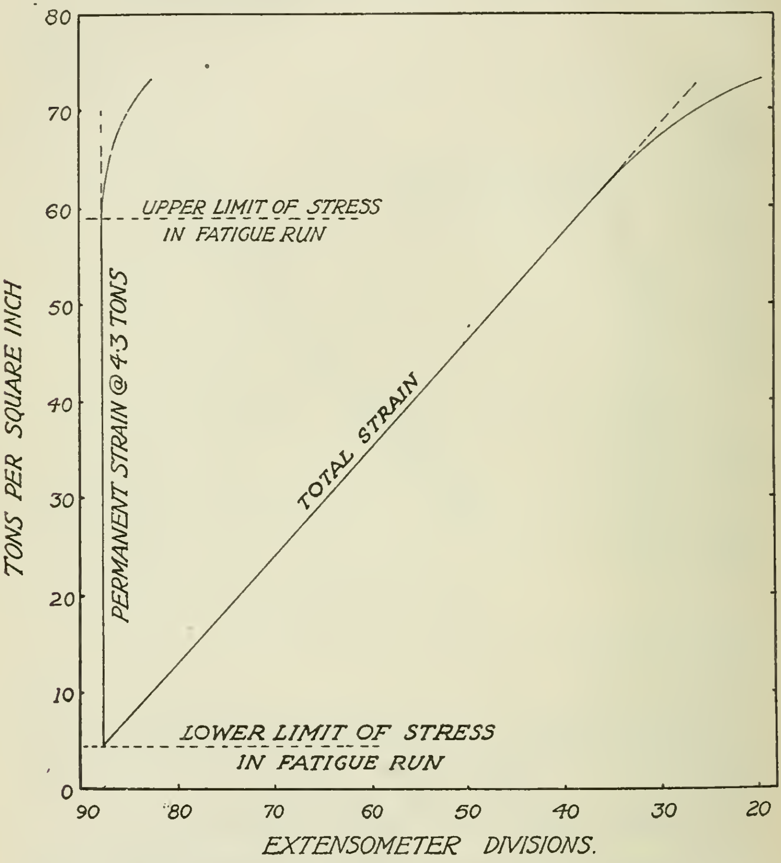

Fig. 20.—Air-hardening steel tested after fatigue stressing.

that quite a few stress cycles produce the necessary raising of the limit of proportionality—a result which is in accordance with the application of static stresses to the material, as shown in Table XXIV.

Some similar determinations have been made upon the cold-worked steel bar D. In the first series of tests the static properties of the metal were examined on samples that were in the fully work-hardened state and on samples that had been blued at 400° C., which is approximately the temperature that produces the optimum value of the limit of proportionality. The samples were subsequently submitted to fatigue tests and measurements made thermometrically to show the evolution of heat produced in the steel during stressing, as was done during the corresponding tests on the quench-hardened steels.

The results of the static test on the fully worked sample are shown in Fig. 21, which gives the load/extension curve and the curve for load/inelastic strain. A complete hysteresis loop is also shown for this material for a range of stress up to a value that is much higher than the limit of proportionality, but not so high as the proof stress. It is to be noted that this loop is closed in the sense that it returns at the minimum load to the original strain value. This loop was obtained after the specimen had been loaded for seventeen hours at a stress of 43 tons per square inch.

After going through the tension test, the specimen was submitted to a fatigue stress fluctuating between 4·2 and 42·5 tons per square inch, and the heat evolution constantly measured during the progress of the test. The curve for the heat evolution is shown in Fig. 22 (A). There was evidently a fairly large evolution of heat at the commencement of stressing, the specimen thereafter showing a reasonably constant heat evolution up to the time of fracture. The stress in fatigue that was applied to this specimen was actually greater than the fatigue limit of the material.

A second specimen was then submitted directly to the fatigue stress without being previously stressed in static tension. The thermal behaviour of this specimen is shown in curve B in Fig. 22. In this sample there is no large original evolution of heat as with the first specimen, and the amount of heat evolved at any stage of the stressing is not so great as with that specimen. The evolution of heat increases towards the time of fracture.

With the material that had been blued at 400° C. similar tests were carried out. The results of the static test are shown in Fig. 26 by means of the load/extension and the load/inelastic extension curves. The difference in the limit of proportionality of the worked and the blued material is obvious, the value for the blued steels being very much higher than that of the material not blued. A hysteresis loop is shown of the steel taken upon

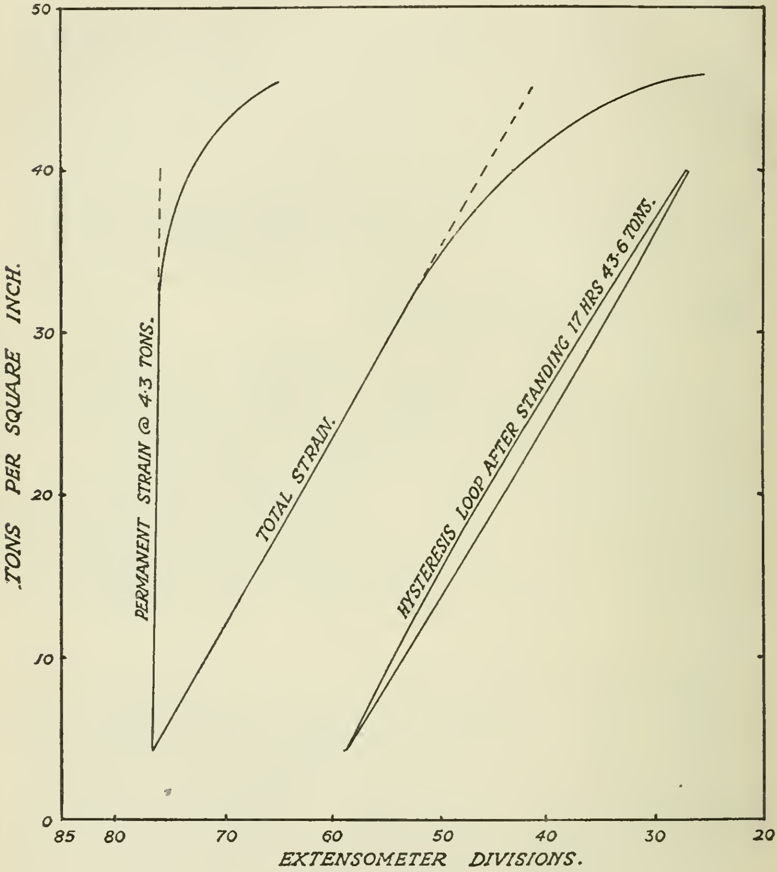

Fig. 21.—Cold-worked steel not previously stressed.

the specimen that had been stressed at 51·7 tons per square inch for twenty hours. The area of this loop is markedly smaller than that of the corresponding loop made on the unblued steel.

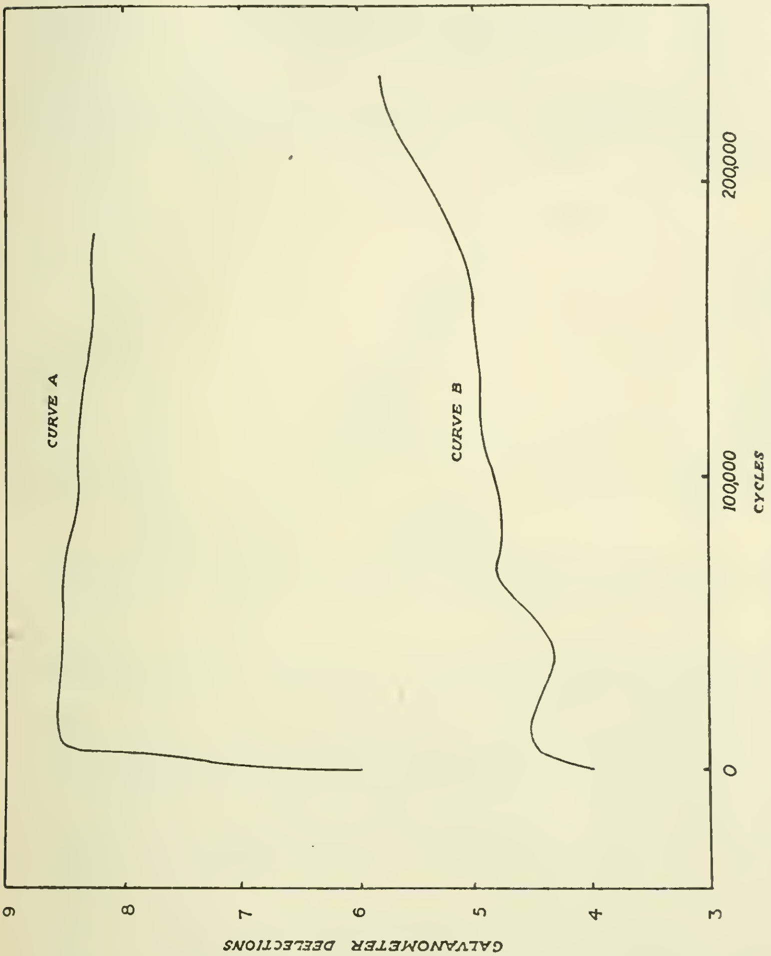

FIG. 22.—Curves showing the heat evolution during the progress of fatigue stress in cold-worked steel (B) or worked (A) after statically stressing.

A second specimen of blued steel was treated in the same way as the second specimen of fully worked steel, by the application of a fatigue stress fluctuating between 4·2 and 42·6 tons per square inch. During the stressing the evolution of heat was measured as before. The observed results are shown in curve C in Fig. 23. The heat evolution is most markedly less with the blued steel than with the material not blued. In general terms this result indicates a much superior stability in the blued steel than in the fully worked steel. This stability can only be a physical or mechanical stability, as any instability of the worked steel cannot be constitutional. The test is, therefore, definite evidence in favour of the intimate connection between the low limit of proportionality of the cold-worked steel and the physical or mechanical instability of the metal. Probably the low value of the limit of proportionality is accounted for with sufficient completeness in this way.

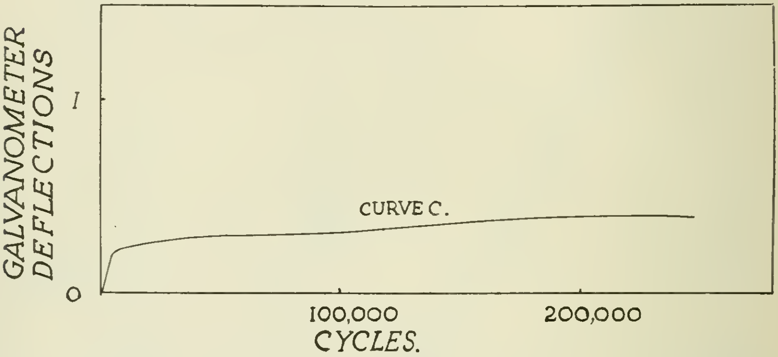

Fig. 23.—Heat evolution during fatigue stressing of cold-worked steel after blueing.

The next set of tests was to determine the effect of the application of the fatigue stresses upon the value of the static limit of proportionality. To do this a sample of the fully work-hardened bar D was submitted to a fluctuating fatigue stress between the limits of 0 and 45·1 tons per square inch. The stress was applied for 20,000 cycles. When the stress was stopped, the load/extension and the load/inelastic extension curves were taken. They are shown in Fig. 24. The curves show that the limit of proportionality of the steel after stressing in this way is actually lower than that of the steel before stressing. This result is of course quite the reverse of that obtained with the air-hardening steel and is therefore of special interest.

Another matter of conspicuous interest that is shown by this test is that the curve showing the relationship between stress and elastic strain is not a straight line, but is curved. The actual curve—that may be obtained by taking the difference between the total strain and the inelastic strain—is shown in Fig. 24. This result is an indication that a material may be elastic and yet not obey Hooke's Law of Proportionality. This may not be a surprising result, but is certainly an interesting one.

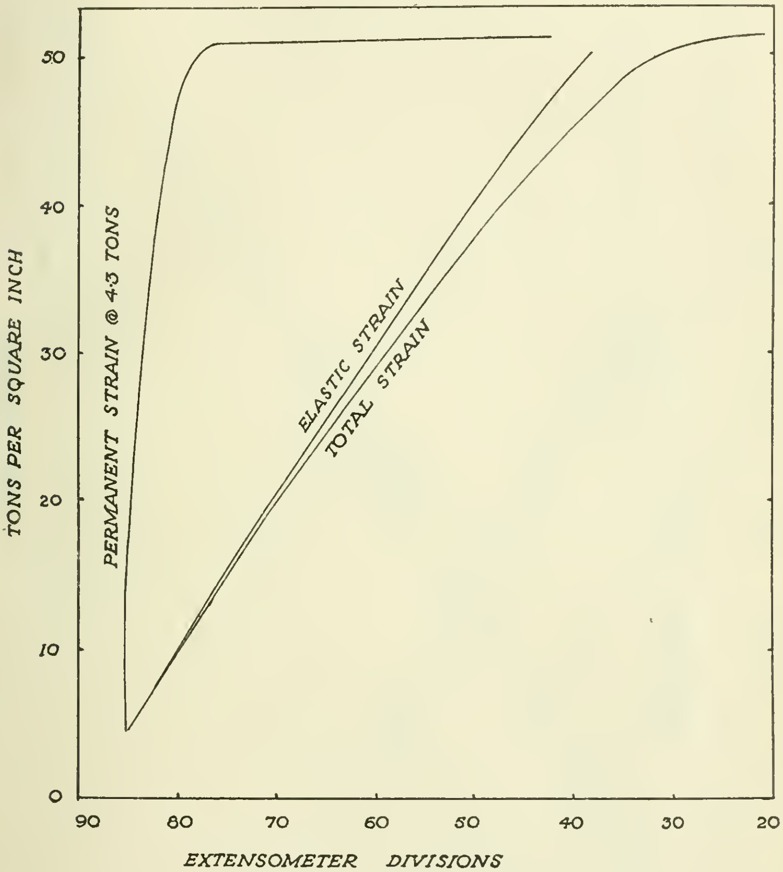

Fig. 24.—Cold-worked steel tested after fatigue stressing.

A second test was made upon the cold-worked carbon steel bar after blueing at 400° C. The sample in this state was

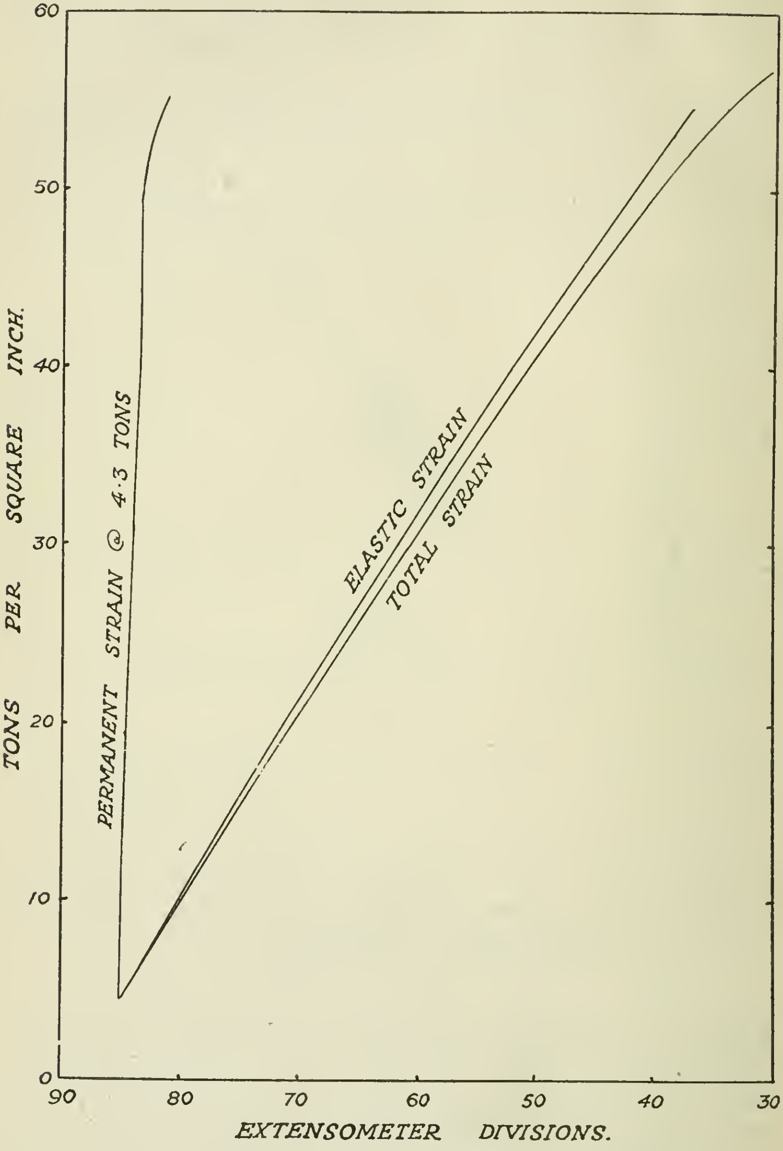

Fig. 25.—Cold-worked steel blued at 400° C. and fatigue stressed.

submitted to a fatigue stress fluctuating between 2·1 and 43·2 tons per square inch for a small number of cycles. The number of cycles would have been greater, but it was observed that the steel was undergoing a very slight extension. The loading was therefore stopped and the specimen examined under static loading. As with the fully worked material, the application of the

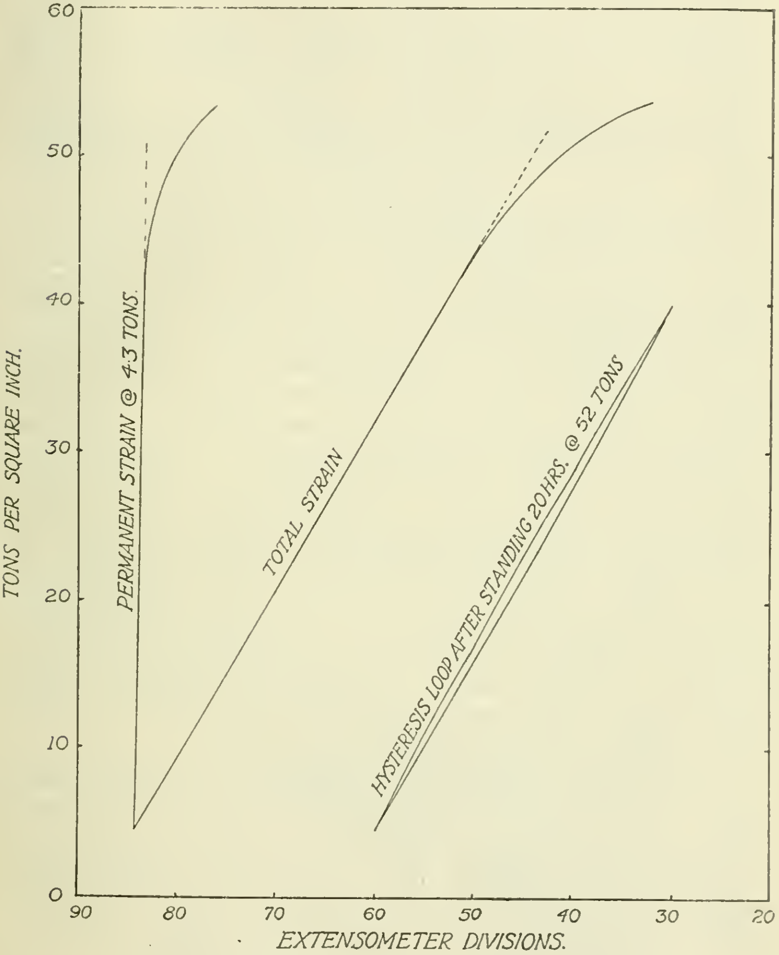

FIG. 26.—Cold-worked steel after blueing at 400° C.

fatigue stress had reduced the limit of proportionality to a value much lower than that of the blued unstressed specimen. The load/extension, the load/inelastic strain, and the load/elastic strain curves are shown in Fig. 25. In this specimen it is again noticeable that the application of fatigue stresses has not only lowered the limit of proportionality but has resulted in a material that gives a curved elastic line. Naturally under such circumstances it is exceedingly difficult to suggest what the relationship may be between the limit of proportionality and the elastic limit or even what is the value of this latter property.

A third sample was tested in much the same way as the second. It was exposed to 20,000 cycles of a stress varying from 0 to 48·5 tons per square inch. After this treatment a careful static loading was given to determine the effect of this treatment upon the value of the limit of proportionality. Once again it was found that the limit of proportionality was lowered. In fact the steel appeared to show non-proportional strain at very low loads indeed—as with the previous specimens. A hysteresis loop was taken between the limits of 4·2 and 46·8 tons per square inch, showing a closed loop of appreciable width. The area of this loop was constant through 50 cycles. When the loop was taken through a large range of stress—*i.e.*, 4·2 to 49 tons per square inch, so that the upper stress is superior to that which produces a marked inelastic strain—the area was considerably increased. A further increase was produced when the upper limit of stress was raised to 52·3 tons per square inch. The results of these tests are shown in Fig. 27.

It is to be noted that the stresses applied to the work-hardened steel in all these tests are a little greater—though not very much—than the fatigue range. The same treatment was given to the quench-hardened steel. With such steel the treatment given raised the apparent elastic limit, whilst with the work-hardened steel the treatment lowered the apparent elastic limit.

Magnetic Tests.

It is quite possible that the low value of the limit of proportionality of the hardened steels might very well be connected with some constitutional property thereof, the constitution and

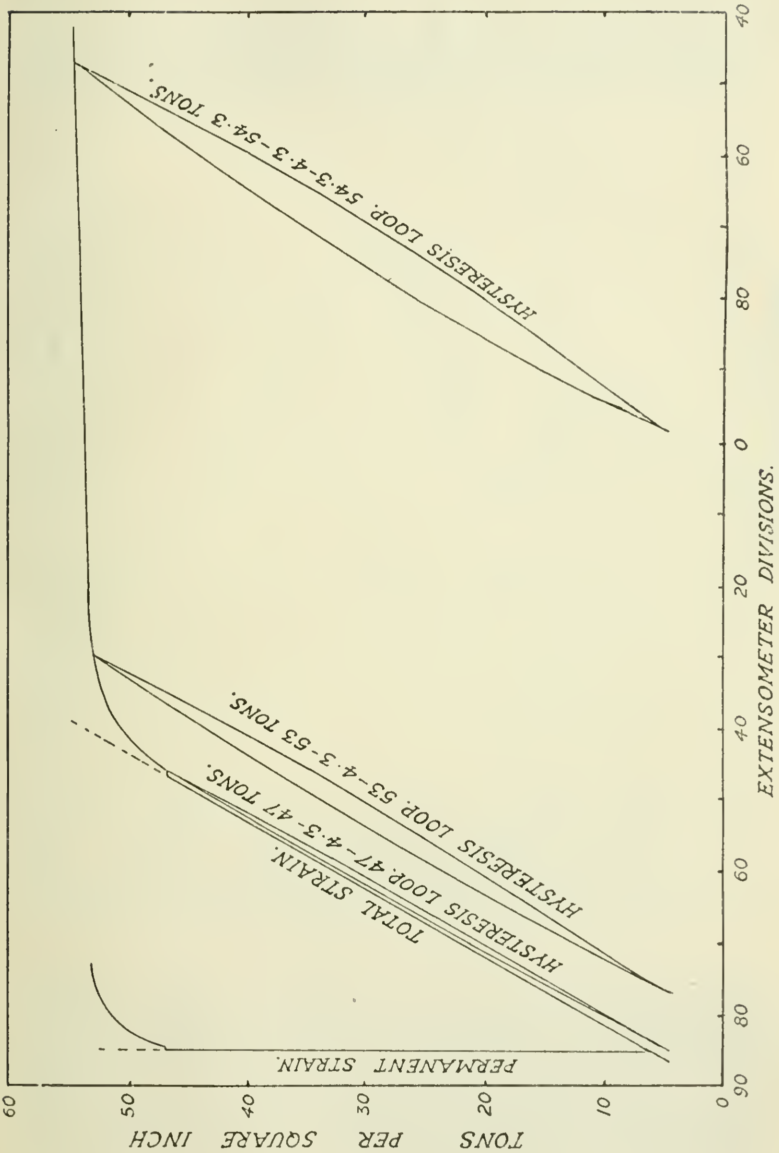

Fig. 27.—Cold-worked steel blued at 400° C. and fatigue stressed.

the value of the limit of proportionality being modified together by the subsequent reheating to relatively low temperatures. For many purposes the microscopical examination of a steel provides good evidence of constitutional changes. For the kinds of steel under investigation this method is practically valueless. The constitutional alterations in the cold-worked steel (if any do occur) cannot be seen by microscopic means. In the nickel-chromium steels, whilst it is reasonably certain that some such changes do take place within the important range of reheating temperatures, the microscope does not give any clear indication of their nature. Other methods, contributory to microscopical examination, must therefore be used if any reliable information

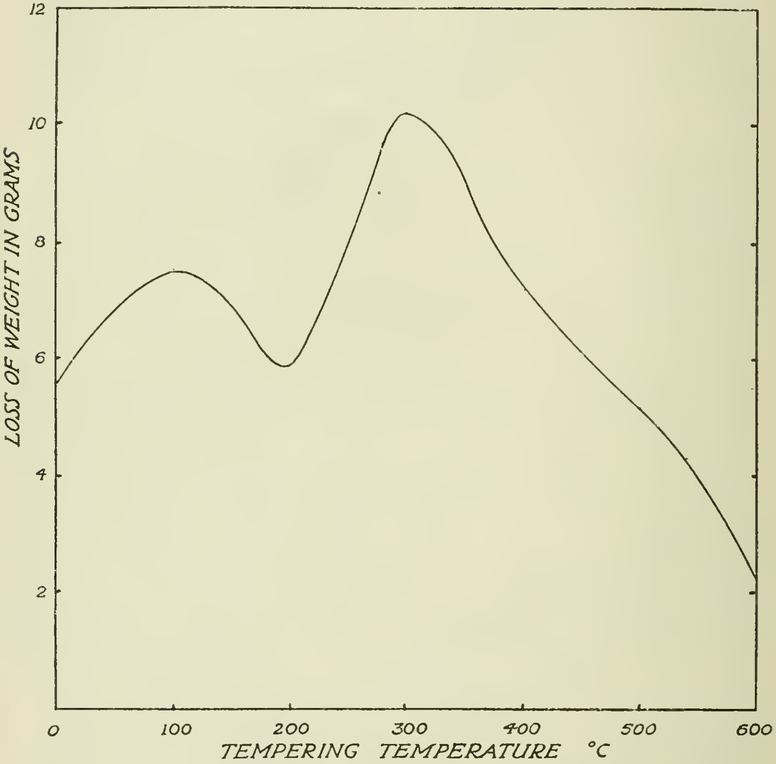

Fig. 28.—Curve showing loss of weight in acid of air-hardening steel tempered at different temperatures.

is to be obtained with respect to the constitutional changes that are produced by and during the simple reheating process. One of the methods that has been employed is an investigation of the magnetic properties of the steel before and after treatment.

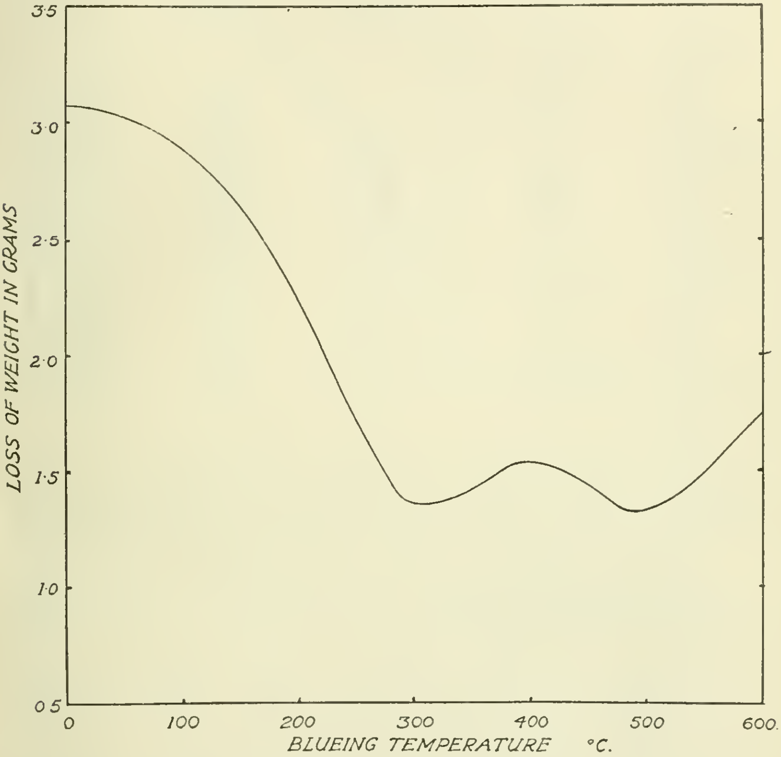

Fig. 29.—Curve showing loss of weight in acid of cold-worked steel blued at different temperatures.

The magnetic properties have been investigated by two different processes. By the first method a crude determination has been made of the intensity of magnetism of the steel B in various conditions, by subjecting specimens of the steel, both as hardened and after reheating to various temperatures, to the influence of a definite magnetic field of constant value, and measuring the mass which the various magnetised bars will support. In Table XXX. are shown the results obtained by this method of examination which is necessarily somewhat approximate.

The results in the table indicate that there is some similarity between the curve (see Fig. 5) which shows the relationship between the limit of proportionality and the temperature to which the steel has been reheated, and the curves which show the relationship between the reheating temperature and the intensity of magnetisation. The latter curves are shown in Fig. 30. Two series of tests were made upon duplicate sets of specimens with different magnetic conditions.

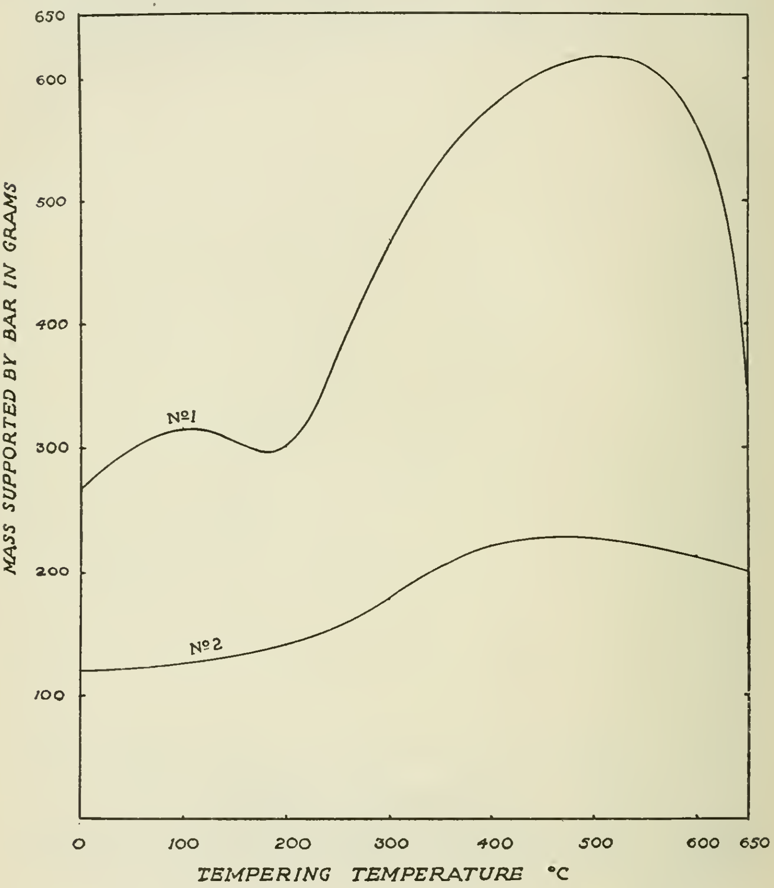

Fig. 30.—Air-hardening steel tempered at various temperatures.

Table XXX.—*The Intensity of Magnetisation of Air-hardened Steel Strip B before and after Tempering at Different Temperatures.*

Mark.	Hardening Temperature. ° C.	Reheating Temperature. ° C.	Mass supported by Bar. Grammes.	
			1.	2.
BM1	830	...	266	...
BM2	830	...	...	120
BM3	830	100	315	...
BM4	830	100	...	129
BM5	830	200	300	...
BM6	830	200	...	142
BM7	830	300	469	...
BM8	830	300	...	175
BM9	830	400	574	...
BM10	830	400	...	219
BM11	830	500	617	...
BM12	830	500	...	222
BM13	830	600	565	...
BM14	830	600	...	212
BM15	830	650	344	...
BM16	830	650	...	136

In the second magnetic method of examination, precise determinations were made of the fundamental magnetic properties of the nickel-chromium steel A and the cold-worked steel D. (In regard to these determinations I have to thank Professor S. R. Milner, Mr. S. H. Seville, and Mr. Shephard for their great assistance.) The full magnetic inductance curve and the hysteresis loop of the steel treated in the usual different ways have been determined upon various samples in different conditions of heat treatment. The values for the permeability at different field strengths have also been extracted. The first series of tests were made upon the air-hardening nickel-chromium steel bar A. This steel was first tested in (i) the fully air-hardened condition, the hardening temperature being 830° C. (specimen AM1), (ii) after reheating to a temperature of 300° C. (specimen AM2), and (iii) after reheating to a temperature of 600° C. (specimen AM3).

In Table XXXI. are shown some of the results of the magnetic tests—in the shape of the values for the remanence, the coercivity, the product of the remanence and the coercivity, and the hysteresis loss in ergs per cubic centimetre per cycle.

Table XXXI.—*Magnetic Values obtained on Air-hardening Steel Bar A after Different Heat Treatments.*

Mark	B.rem.	H.c.	B.rem × H.c.	Ergs per c.c. per Cycle.
AM1	7,800	12·8	99,500	$5{\cdot}09 \times 10^3$
AM2	11,200	28·8	324,000	$17{\cdot}50 \times 10^3$
AM3	12,300	17·6	217,000	$8{\cdot}30 \times 10^3$

It is desirable also to show the value of the permeability for the various specimens at different values of the magnetising field. The values for the three specimens already dealt with are shown in Tables XXXII. to XXXIV., the values being taken up to the magnetic " saturation " point.

Table XXXII.—*Permeability at Different Values of H for fully Air-hardened Nickel-Chromium Steel.* (*Specimen AM*1.)

H (Gausses).	Permeability.
9·45	48·5
14·3	56·0
26·9	71·5
69·1	143·0
115·0	110·0
124·5	100·5
148·0	93·0
165·0	84·0
201·0	70·9

Table XXXIII.—*Permeability at Different Values of H for Nickel-Chromium Steel Bar Hardened in Air and Tempered at* 300 ° *C.* (*Specimen AM*2.)

H (Gausses).	Permeability.
8·4	99
12·5	106
21·8	131
47·0	267
82·0	195
132·0	138
165·0	109

TABLE XXXIV.—*Permeability at Different Values of H for Nickel-Chromium Steel Bar Hardened in Air and Tempered at* 600° *C.* (*Specimen AM*3.)

H (Gausses).	Permeability.
9·1	135
13·2	280
15·6	660
46·0	382
108·0	171
138·0	138
169·0	114

The values for the change of permeability with varying values of H are plotted diagrammatically for the three specimens AM1, AM2, and AM3, in Fig. 31.

The results given in Tables XXXI. to XXXIV. are interesting and indicate that the mere rebeating of the hardened steel to such a temperature (*i.e.* 300° C.) as does not alter the maximum stress very appreciably, but which does markedly affect the limit of proportionality by raising it, brings about a very decided alteration in the magnetic properties of the steel.

It has already been shown that the effect of reheating the air-hardening nickel-chromium steel for a prolonged period at a temperature as low as 100° C. is to produce a very marked change in the limit of proportionality—approximately as great as is produced by reheating the steel to the optimum temperature. The results of magnetic tests on a sample of the steel A that has been treated in this way (marked AM4) are given below. This specimen was maintained at 100° C. for a week, after hardening in air from 830° C., and had the following magnetic properties :

B.rem.	7,200
H.c.	28·8
B.rem. × H.c.	207,500
Ergs per c.c. per cycle	$15 \cdot 12 \times 10^3$

The values for the change of permeability of this specimen produced by alteration in the value of H are shown in Table XXXV. and in Fig. 32.

TABLE XXXV.—*Permeability at Different Values of H for Nickel-Chromium Steel Bar Hardened in Air and Tempered at* 100° *C. for a Week.* (*Specimen AM*4.)

H (Gausses).	Permeability.
10·5	47·1
14·1	49·0
22·8	62·5
50·0	115·0
97·0	115·0
138·0	97·0
178·0	81·0

It is to be noted that the prolonged heating at 100° C. has produced comparatively little alteration in the permeability of the steel (compare Fig. 31), although it has produced a definite and marked change in its limit of proportionality and also in some of the other magnetic properties—notably the coercivity which has been very markedly increased. Naturally the increase in this value is reflected in its product with the remanence and also in the hysteresis loss per cycle.

In view of the result of the last experiment, it was considered desirable to test what effect would be produced upon the magnetic properties of the hardened steel by the application of a definite stress to the steel. Accordingly, therefore, specimen AM5 of the air-hardening nickel-chromium steel bar A was stressed to a value definitely higher than the highest value of limit of proportionality that could be obtained from such steel after tempering at the optimum temperature. The actual stress applied to the specimen was 60 tons per square inch in tension. The magnetic properties of the specimen after such treatment were :

B.rem.	8,600
H.c.	32
B.rem. × H.c.	276,000
Ergs per c.c. per cycle	$18 \cdot 9 \times 10^3$

The variations in the permeability produced by alterations in the value of H for specimen AM5 are shown in Table XXXVI. and in Fig. 33.

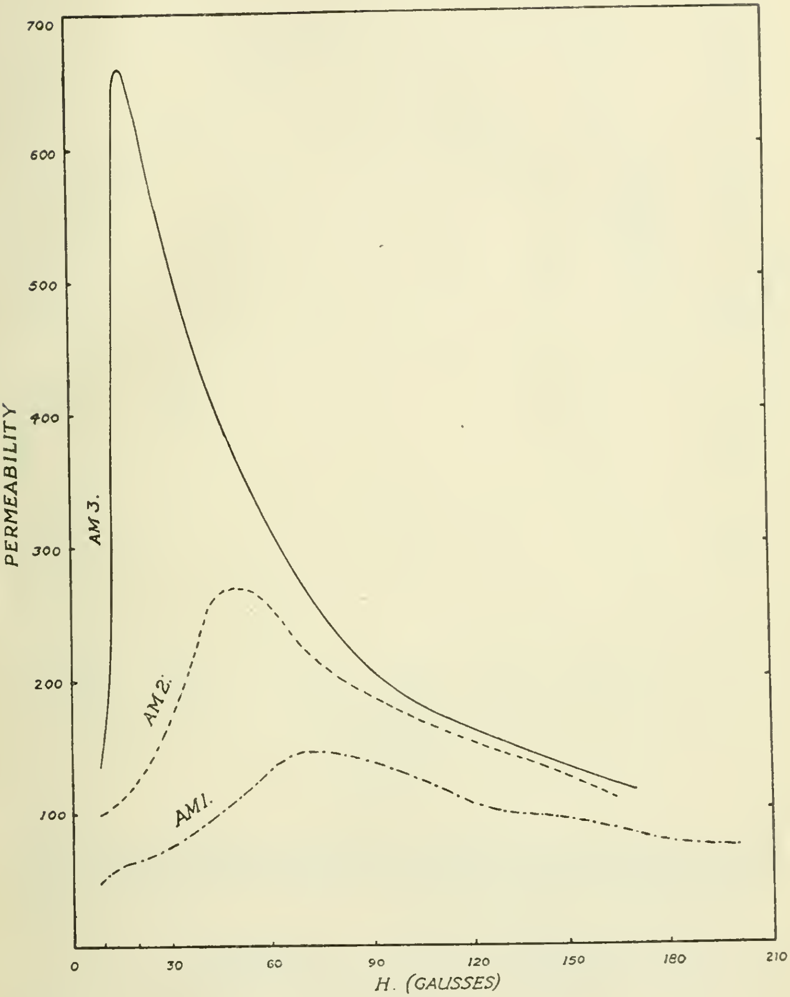
700
600
500
400
300
200
100
PERMEABILITY
AM 3.
AM 2.
AM 1.
0
30
60
90
120
150
180
210
H. (GAUSSES)

Fig. 31.

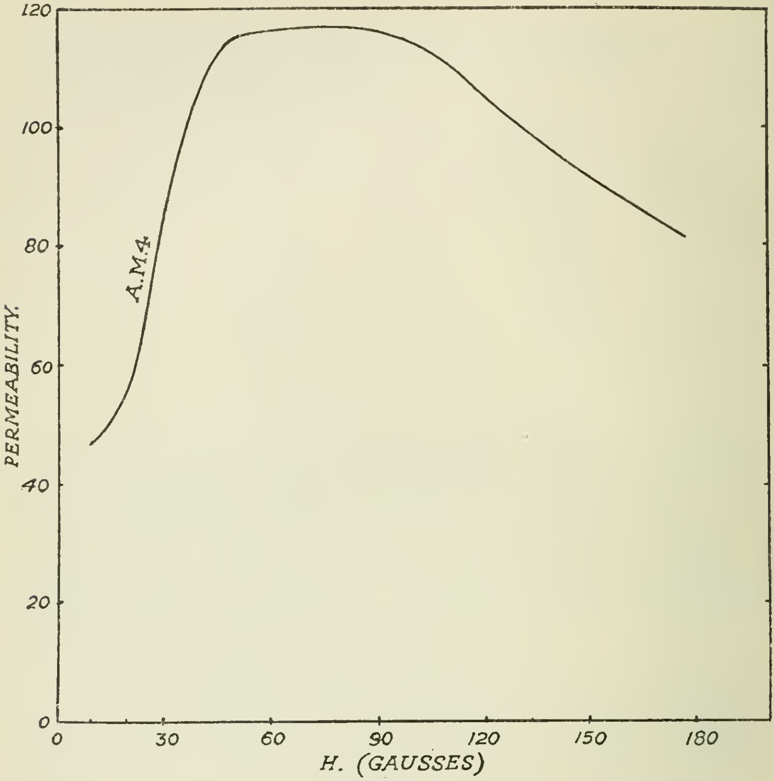

FIG. 32.

TABLE XXXVI.—*Permeability at Different Values of H of Nickel-Chromium Steel Bar Hardened in Air and Stressed at* 60 *Tons per Square Inch.* (*Specimen AM*5.)

H (Gausses).	Permeability.
9·4	50
14·2	53
23·5	61
46·2	125
89·0	134
122·0	112
157·0	94

As occurred in the test on the material maintained for a prolonged period at 100° C. the stressed steel has a permeability curve that varies but slightly from that of the steel in the fully hardened state.

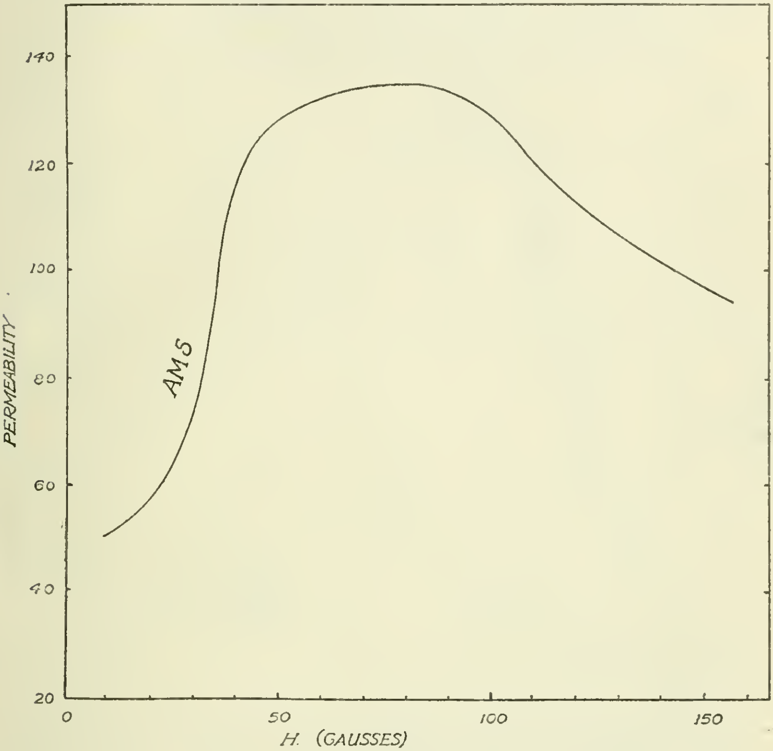

Fig. 33.

It is noteworthy that the greatest alteration in magnetic values produced by this application of stress is shown in the increased value of the coercivity—just as occurred in the specimen that was reheated to 100° C. for a long time.

To facilitate comparison, the permeability curves of the air hardening steel bar as fully hardened, after tempering at 100° C. for a week, and after stressing at 60 tons per square inch, are shown together in Fig. 34.

The magnetic test results obtained upon the air-hardening steel in its various conditions provide useful information. Similar experiments were therefore made upon the cold-worked steel bar D. It was not expected that the alteration of the limit of proportionality produced by reheating such a steel would be very markedly reflected in the magnetic properties of the steel before and after blueing, and this was confirmed substantially by the actual test results. Two specimens of the cold-worked bar were tested, one in the fully work-hardened condition (DM1) and the other after blueing at 400° C. for half an hour (DM2). The results obtained upon these two specimens were as follows :

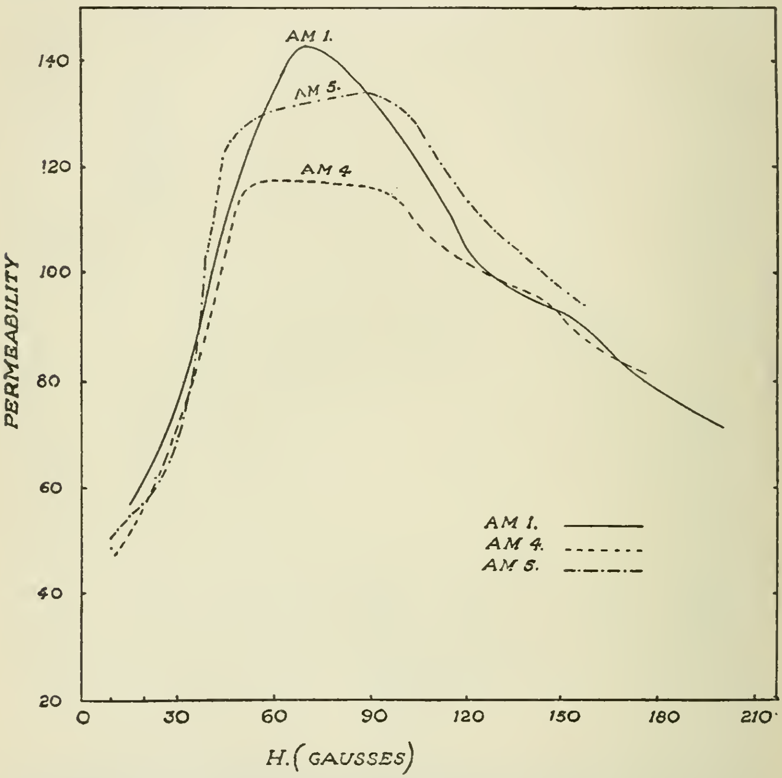

FIG. 34.

	Specimen DM1. Work-hardened.	Specimen DM2. Blued at 400° C.
B.rem.	10,800	11,700
H.c.	29	34
B.rem. × H.c.	310,000	395,000
Ergs per c.c. per cycle . .	$17 \cdot 1 \times 10^3$	$20 \cdot 3 \times 10^3$

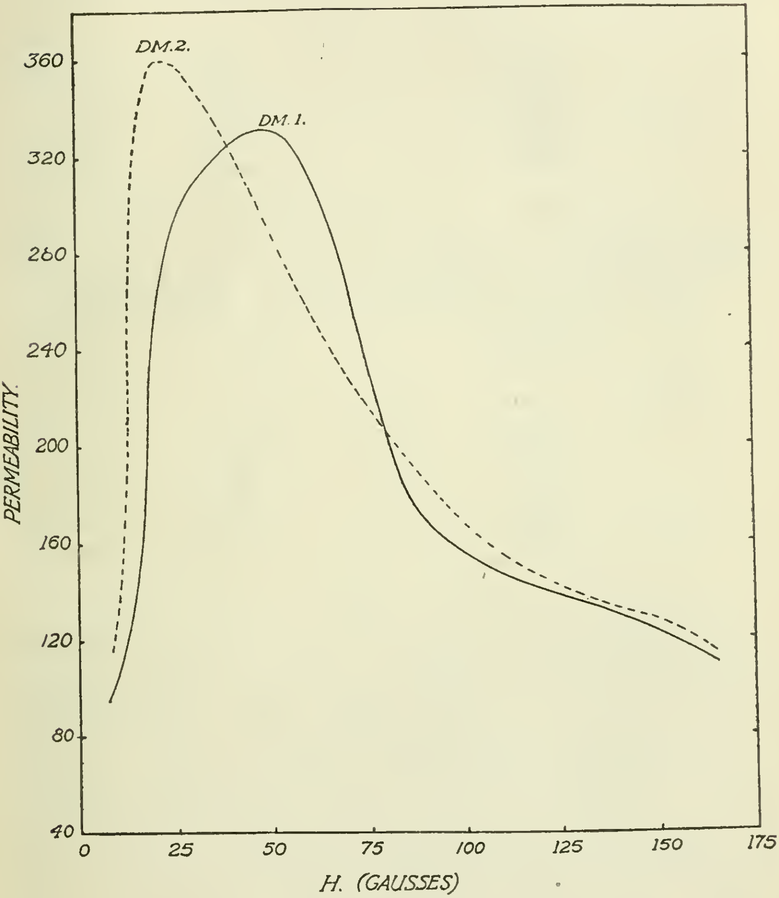

FIG. 35.

In Tables XXXVII. and XXXVIII. are set out the values of the permeability of the two specimens DM1 and DM2 for varying values of H up to the "saturation" point. The permeability curves are shown in Fig. 35.

Table XXXVII.—*Permeability at Various Values of H of a Cold-worked Steel Bar as fully worked.* (*Specimen DM*1.)

H (Gausses).	Permeability.
8·3	95
13·4	123
21·6	266
46·2	330
91·5	166
130·0	136
165·0	109

Table XXXVIII.—*Permeability at Various Values of H of a Cold worked Steel Bar after Blueing at* 400° *C.* (*Specimen DM*2.)

H (Gausses).	Permeability.
9·3	117
13·4	210
21·6	360
46·7	304
92·0	180
132·0	136
164·0	115

The results of the various tests show that the effect upon the magnetic properties of blueing the cold-worked carbon steel at a temperature that materially alters its limit of proportionality is not very great. The values of the remanence and coercivity are both increased, whilst the permeability for fields of low and moderate intensity is raised. On the whole there is, however, no such marked alteration in properties as is brought about by the reheating of the air-hardening nickel-chromium steel. This is quite in accordance with what would be expected as to the probable effects of reheating upon the constitutional properties of a cold-worked steel and a "quench-hardened" alloy steel. In the former there is constitutional stability but physical instability, whilst in the latter there is both constitutional and physical instability. The magnetic tests are in line with the other tests on these steels in giving these results.

Constitutional Tests.

With such steels as are being considered, it is practically hopeless to look to microscopic examination for assistance in regard to structural changes. In the alloy steels there is no doubt whatever that certain structural changes are proceeding during the reheating (tempering), and what these are may be generally surmised. It is known that the nett effect of the tempering operation is to transform the martensite and austenite that is originally present in the hardened specimens into troostite and/or sorbite, the latter being the ultimate product of the tempering operation. Probably also the change of austenite into sorbite occurs in two stages by the formation first of martensite, though this may be almost momentary, which in its turn passes into sorbite. The progress of these constitutional changes cannot be observed microscopically, however, and the evidence of the truth of this explanation must rest upon other grounds. Observations of the microstructure have been made during the present experiments with the negative result that was to be expected. A well-recognised auxiliary test for constitutional changes is that of examining the extent to which loss of weight occurs when the different materials are exposed to the attack of a fairly dilute acid. This method was employed by Heyn and Bauer and also by Benedicks (amongst others)—the former giving particular results on cold-worked steels and the latter on hardened and tempered steels.

In the first series of such tests, specimens of the nickel-chromium steel strip B have been examined. After receiving the appropriate heat treatment, which was carried out in approximately the finished dimensions of the specimen, the test-pieces were brought to a uniform dimension and were cleaned thoroughly, washed with alcohol and then with ether, dried and weighed. They were then suspended in a beaker of 10 per cent. sulphuric acid for twenty-four hours. Each specimen was suspended in a separate vessel. After the attack the specimens were removed, cleaned gently but thoroughly, again washed, dried and weighed. The solution of ferrous (and ferric) sulphate resulting from the attack upon each specimen was analysed to determine its iron content, which therefore constituted a check and a correction of the information obtained from loss of weight measurements. The tests throughout were made in duplicate, and the results obtained, given as the mean of the duplicate samples for each treatment, are shown in Table XXXIX., where the loss of weight of the sample and the weight of dissolved iron are both shown.

TABLE XXXIX.—*Loss of Weight in Acid of Air-hardening Nickel-Chromium Steel Strip before and after Tempering at Various Temperatures.*

Tempering Temperature. ° C.	Mean Loss of Weight of Sample, in Grammes.	Weight of Iron in Resulting Solutions, in Grammes.
...	5·53	5·12
100	7·52	6·96
200	5·82	5·36
300	10·22	9·36
400	7·26	6·63
500	5·18	4·73
600	2·17	1·93

The curves indicating these test results are shown in Fig. 28. It is interesting to note the effect of the tempering temperature upon the ease with which the materials go into solution. It is also interesting to note that the general form of the curve of the solubility curve is remarkably similar to the general form of the curve that connects the tempering temperature and the limit of proportionality. Lest any too hasty conclusions should be drawn from this general resemblance, it would appear desirable to indicate briefly what the factors are that might influence the form of the solubility curve. As these facts are sufficiently known to be accepted in general, no arguments need be adduced here in their support. Solubility may be affected by: 1. The chemical nature of the individual constituents. 2. The constitutional nature of the individual constituents. 3. The physical condition of the constituents—*i.e.* whether strained or unstrained. 4. The juxtaposition of two or more different constituents having different electrochemical properties. 5. The physico-chemical condition of the constituent or constituents—*i.e.*, whether crystalline or colloidal or a mixture.

Within the different samples of alloy steel that were examined various of these factors come into play, because of the possible variety of the conditions that exist within the steel. Briefly stated, the actual conditions of the alloy steel that must be regarded are: 1. That the steel as hardened contains at least two constituents, martensite and austenite, of different constitutional characteristics. 2. That during the tempering operation the austenite passes into martensite. 3. That by tempering, the martensite is transformed into troostite and thence into sorbite. 4. That troostite is of a different physico-chemical nature from either martensite on the one hand, or sorbite on the other. 5. That the existence of austenite in the metal argues a state of strain, the degree of strain being probably different in different crystals of the complex. 6. That the state of strain in the metal is relieved by tempering and is probably removed at a temperature lower than that at which the steel is put into a purely sorbitic condition, and further is probably reduced to innocuous proportions when the austenite has been completely transformed either into martensite or further into troostite. 7. That in the intermediate stages of tempering the steel may consist of three constituents, austenite, martensite, and troostite, but at the completion of the tempering of only one constituent, *i.e.*, sorbite. 8. That in sorbite there are two constituents largely in a condition parallel to that of a partially coagulated colloid, and therefore in a state which has a lower tendency towards solution than the troostite from which it was formed.

These factors mean that the solubility of the steel is likely to be increased by: 1. The formation of troostite. 2. The presence of strains due to the austenite-cum-martensite structure. 3. A marked heterogeneity of constitution—and is likely to be decreased by: 1. The actual existence of any marked proportions of austenite crystals (as they themselves have a relatively low solubility). 2. The removal of strains. 3. The presence of sorbite in large proportions. 4. An increased homogeneity of the constitution of the metal.

Regarding the actual test results then, it becomes plain that the slight solubility of the fully tempered steel may be attributed to the presence of an unstrained material consisting entirely of sorbite. The high solubility of the steel tempered at 300° C. is due to the presence of a large proportion of troostite and the decreasing solubility of the steel as the tempering temperature rises from 300° to 600° C. to the replacement of the troostite in a greater or less measure by sorbite. The relatively low solubility of the steel in the fully hardened condition represents the existence of a steel that consists largely of martensite and austenite, neither of them having a very high intrinsic solubility, that of the martensite being distinctly greater than that of the austenite. The subsequent increase of solubility after tempering to 300° C. represents the transformation of the metal from the austenitic and martensitic state to the troostitic.

The evidence provided by the solubility determinations is evidently slight in regard to the relationship between constitution and the value of the limit of proportionality. The evidence of these experiments must be regarded alongside that provided by the magnetic experiments. This is postponed to the summing up given below. It can be said safely that there is one obvious conclusion to be drawn here and that is that a steel in the troostitic or sorbitic state has a high value of the limit of proportionality, and that the limit of proportionality rises as the steel is transformed into the troostitic condition. As regards changes at lower tempering temperatures this method of examination does not provide any striking evidence.

Similar tests were made upon the cold-worked steel strip E in the hope of supplementing the more direct observations that could be made of constitutional and other changes. Strips of the steel were prepared in the same way as the specimens of the air-hardening steel. The specimens used were as fully work hardened, and after blueing at temperatures of 100, 200, 400, 500, and 600° C. respectively. The method of testing coincided with that used for the nickel-chromium steels. The results of the observations upon the cold-worked steel are given in Table XL. and Fig. 29.

The interpretation of the results obtained upon this cold-worked steel can be made more simply than for the alloy steel previously considered. In the cold-worked steel there are no structural changes, ordinarily so called, to be taken into account until the reheating temperature has risen to about 500° C.—*i.e.*, to a value considerably higher than that which produces the optimum value of the limit of proportionality. Microscopically the steel undergoes no alteration up to temperatures of 400° C.

or more. The absence of microscopic evidence in this steel is not due to the difficulty of observation or to the masking of the effects by secondary causes. The microstructure is plain and obvious at all stages of the heating. If, therefore, it becomes evident that the steel is undergoing any change, then that change must either be of a submicroscopic order—if it is constitutional in the ordinary sense of the term—or be constitutional in an unusual sense, or else not be connected with the constitution at all. The alteration of the limit of proportionality of the steel during the process of blueing is in itself an indication of some change that is going on in the steel, but this may well be connected with the physical or mechanical condition of the metal rather than with its chemical or metallurgical state.

TABLE XL.—*Loss of Weight in Acid Solutions of Cold-worked Strip Steel E before and after Blueing at Various Temperatures.*

Mark.	Reheating Temperature. ° C.	Loss of Weight in Grammes.
EW1	...	3·09
EW2	100	2·89
EW3	200	2·25
EW4	300	1·35
EW5	400	1·54
EW6	500	1·32
EW7	600	1·76

The curve showing the relationship between loss of weight and blueing temperature runs in a direction almost directly opposite to that of the curve showing the relationship between the limit of proportionality and the reheating temperature for the work-hardened steels. The most obvious explanation of the former curve is that the variation in the loss of weight is mainly determined by the presence or absence of strain or strain products in the metal—a condition that is well known to influence profoundly the solubility of a metal. There is a consistent decrease in solubility during the early stages of the reheating process which may well be interpreted to mean a consistent removal of strain from the steel. The behaviour of the material after tempering at temperatures over 400° C. is unimportant so long as it does not in any way discredit the explanation put forward in respect of the earlier behaviour. Clearly it does not.

The evidence of the experiments upon loss of weight on the cold-worked steels is to indicate that with tempering at higher and higher temperatures the steel is being constantly denuded of its strain. This would accord perfectly with the results of the determinations of the limit of proportionality after similar heat treatments.

With the cold-worked steels it was quite possible to make observations to examine for the first appearance of slip lines under tension stress. A specimen of a cold-worked steel strip was loaded under increasing tension in the testing machine and kept under microscopic observation during the whole of this time. The specimen had previously been polished and etched lightly. Contrary to expectation there was no visible evidence of slip lines until a stress higher than the proof stress had been applied to the material. At stress values above this—*i.e.* corresponding nearly with what would be regarded as the yield point, the formation of slip bands was quite evident. Very careful searching of the specimen at stresses below the proof stress and slightly above failed to discover any sign of slip bands. When the slip bands did appear they came in the normal way (see Fig. 38, Plate XII.). It has transpired that similar observations were made by Mr. Adam, of Messrs. Bruntons, Musselburgh, in connection with his recent report upon cold-worked steels, and the following kind communication for insertion herein indicates the conclusion formed by Mr. Adam. The photomicrographs referred to in this report are shown in Figs. 36 and 37 (Plate XI.). The conclusions reached by Mr. Adam appear to be very similar to those arrived at in this investigation, and not at variance with the observations of other workers upon the formation of slip lines. The distortion of the pearlite referred to by Mr. Adam was not observed in the present examination.

"We have carried out some experiments on somewhat similar lines to those suggested. In the first instance by carrying out a tensile test under microscopic examination. The idea we had in view was to find if the microscope would reveal some evidence of permanent deformation in cold-worked steel before the yield point was reached. In view of the fact that stress-strain diagrams of steel that has been recently cold-worked show a distinct departure from the straight line at a comparatively low stress, we thought it possible that microscopic examination would reveal some slight evidence of permanent deformation along the same planes of slip already utilised in the previous cold-working. In this respect, however, the results were entirely negative, even under careful survey with an oil-immersion lens. Only a general movement, which appeared to be entirely elastic in nature, was observed until the specimen had taken a decided permanent set. At this point, slip bands appeared, but not until the metal had been distinctly strained did the slip bands appear very extensively. Even after the yield point had been surpassed, the majority of the grains appeared to be unaffected.

" Further experiments were made by examining specimens under alternating stress, but again not until the specimen had been obviously over-strained did the slip bands appear. This does not, of course, mean that there is no permanent deformation below the yield point, but it seems likely that the initial movements are sub-microscopic. Further experiments are contemplated with more perfected apparatus, arranged in such a way as to show the slightest alteration in a structure quite apart from the development of slip bands.

" Two photomicrographs are shown (Plate XI) of the same field of view. Fig. 36 before, and Fig. 37 after deformation under alternating stress.

" The most noticeable feature, apart from the development of slip bands, is the evidence of distortion of the pearlite areas. This rather suggests that the first signs of strain may be looked for in the neighbourhood of the pearlite patches.

" On the other hand, all the specimens we have examined show that the pearlite or sorbite areas almost invariably interrupt a slip band, and that their strengthening effect is mainly due to slip interference."

Two further tests have been made with the work-hardened steels, in order if possible to detect any other change of properties brought about by the reheating to such temperatures as produce the optimum value of the limit of proportionality. The first test was the determination of the specific gravity of the steel in the fully worked state and also after reheating to various temperatures up to 600° C. The values obtained indicate quite plainly that there is no progressive change in the density of the metal, and that the only alteration produced is that which occurs at the temperature of the recrystallisation—*i.e.*, just above 500° C. The mean of the actual values observed are set out in Table XLI. It is evident from these figures that if blueing has the effect of causing a healing of the slip planes, the amount of material thereby affected is by no means large. The change of density during blueing is almost negligible, and is not even of the same order as has been found during the plastic distortion of the metal by other workers. (The values observed here are very similar to those found by Goerens.)

TABLE XLI.—*Density of Cold-worked Strip E before and after Reheating to various Temperatures.*

Reheating Temperature, °C.	Specific Gravity.
...	7·830
100	7·830
200	7·830
300	7·828
400	7·830
500	7·828
600	7·836
850	7·835

The second series of tests that were made involved the determination of n in Meyer's formula connecting the load and the diameter of the impression produced in the Brinell test. The formula $L = ad^n$ is well known, and the exponent is taken usually to indicate the capacity of the material for further cold work. It is generally taken also to represent the degree to which the material has been rendered plastic, as materials that are truly plastic—*i.e.* plasticine or pitch—have a value of n equal to 2. The nearer to 2 that the value of n becomes, the greater the approach to the plastic state. It was thought that there might be some distinct difference between the value of n in the fully worked steel and in the same steel after it had been blued so as to produce the optimum value of the limit of proportionality—

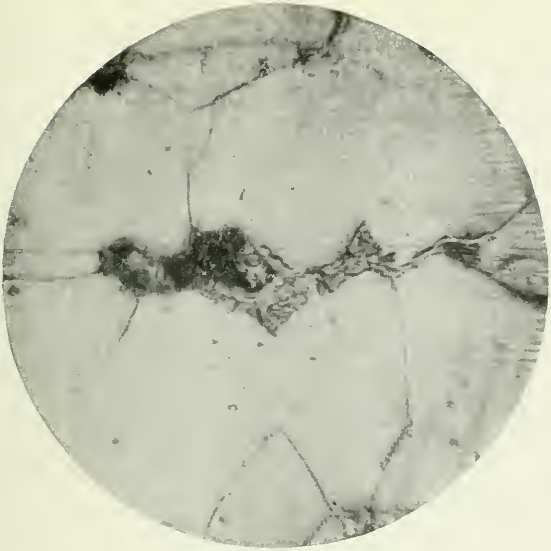

FIG. 36. Before straining. × 1500.
(Adam.)

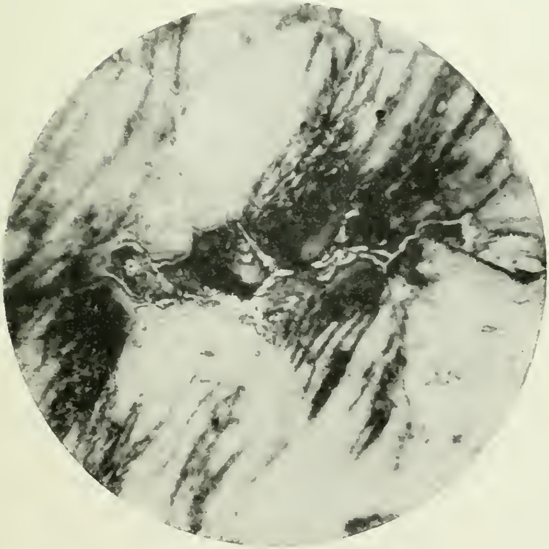

FIG. 37. After straining. × 1500.
(Adam.)

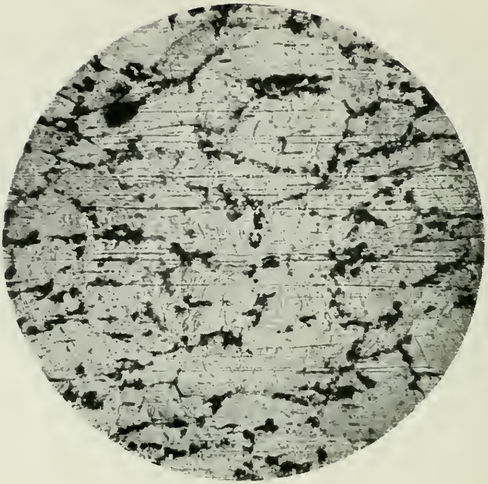

FIG. 38. Showing the slip bands developed in cold-worked Strip E when stressed to the proof stress. × 400.

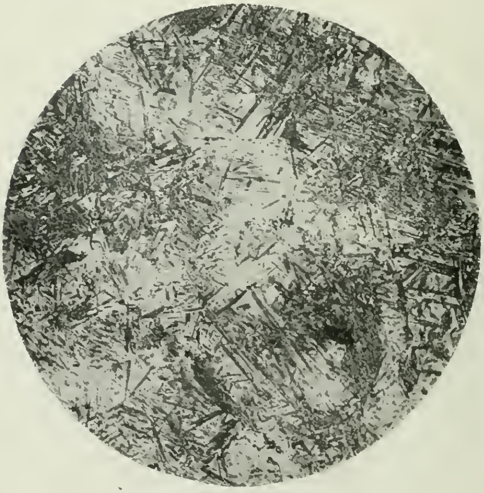

FIG. 39. Showing austenite martensite structure of air-hardened steel. × 500.

particularly if the reheating brought about any marked change in the amount of strain left by the work hardening. Tests were made therefore on the steel as worked and after blueing at different temperatures, and the value of *n* determined. The results obtained are shown in Table XLII.

TABLE XLII.—*The Value of n in Meyer's Formula* $L = ad_n$ *for the Cold-worked Strip E before and after Reheating to Different Temperatures.*

Reheating Temperature, °C.	*n*.
...	2·19
100	2·19
200	2·21
300	2·18
400	2·19
500	2·24
600	2·52
850	2·53

The test results indicate very plainly that there is no noticeable change in the value of *n* until the steel has been heated to the temperature of recrystallisation. The alterations of the limit of proportionality are not reflected in the value of *n*. When the metal softens—*i.e.*, when its maximum stress changes—*n* alters very considerably, but not before. It is very likely that *n* is more connected with plasticity than with elasticity, and therefore that the changes of elastic limit would not affect it. The capacity for further cold work may be reflected by the maximum stress and not by the elastic limit. Clearly also, the amount of plastic material in the worked steel is not so great that an alteration in its quantity can be reflected in the value of *n* in the Meyer formula.

CONCLUSIONS.

In considering the results that have been recorded above with the intention of attempting an explanation of the observed phenomena, it is desirable to separate completely the two main types of steel that have been examined. There appear to be similarities in the reasons for the low value of the limit of proportionality in the cold-worked and the air-hardening steel, but confusion may arise if both steels are dealt with together. It is most convenient to consider the cold-worked steel first.

In regard to this kind of steel, the experiments carried out have given the following results. The steels as worked have a low value of the limit of proportionality, which can be raised to a very much higher value by blueing at a temperature of approximately 400° C. There is a progressive increase of the limit of proportionality of the steel as its blueing temperature is raised from atmospheric temperature to 400° C. Thereafter the value of the limit of proportionality falls off in proportion to the change in the maximum stress. This behaviour is observed when tension stresses are applied to the steel. When a compression load is applied to the material the value of the limit of proportionality of the fully cold-worked metal is not so low as that shown in tension. The value, however, rises markedly when the steel is blued and ultimately attains a value that is practically equal to the optimum value given by the steel when tested in tension after blueing.

The values for the proof stress of the steel, tested in tension, are much higher than might be expected from the low value of the limit of proportionality. This applies particularly to the values obtained in tension. The actual value of the proof stress is varied somewhat by the extent to which the steel has been cold worked. The general result of all the proof stress determinations is, however, to the effect that the value obtained is not considerably affected by the low limit of proportionality—in other words, that the ratio of proof stresses to maximum stress is not very much lower in the fully work-hardened steels than in those that have been blued at a temperature which produces a high value of the limit of proportionality. This statement applies both to compressile and tensile stresses. The proof stress is, of course, an indication of the ease with which a marked inelastic strain is produced in a material. The fact, therefore, that there is but little difference in the value of the proof stress between materials having a high and those having a low limit of proportionality is an indication that the existence of a low limit of proportionality in a steel is not a proof that a large amount of inelastic strain is easily produced within the metal at stresses not very much above the limit of proportionality. This result is confirmed by the result that microscopical examination fails to reveal the existence of any visible slip lines in the metal that has been loaded at stresses between the limit of proportionality and the proof stress. This does not necessarily mean that *no* slip lines are formed in such metal, but that they are certainly not produced in any large number, and therefore that the inelastic strain—even in isolated places—is very small.

The results of the experiments made upon the loss of weight sustained by the steel when attacked by acids show that it behaves in a way that would be explained by the assumption that the steel in the fully worked condition is in a state of physical strain or metastability, which state is altered progressively by heating until the steel loses its strain and passes into a stable condition when blued at a temperature of 300° or 400° C. The factor that enters into this behaviour is that which increases the solution potential of the steel, and this of necessity is the solution potential of the ferrite. Instability in various forms may increase the solubility of ferrite, and it is reasonable to infer that the results definitely indicate the existence of strain or mechanical instability in some form in the work-hardened metal and the absence of this particular form of instability in the blued material. The low limit of proportionality is therefore to be connected with a form of mechanical instability, and the high limit of proportionality with the absence of the form of instability that is present in the work-hardened material. It will be necessary to revert to this point and to consider the type of instability that is likely to be important in producing a low limit of proportionality, because the steel that has been blued at 400° C. is still in a state of instability of some kind, removable only by reheating to much higher temperatures, which consequently brings about a recrystallisation of the material and the assumption of a state that is stable. When this condition is reached the steel has lost its hardness as well as its instability or metastability.

Determinations of the heat evolution during the application of fatigue stresses indicate that a fully work-hardened material produces more heat per cycle of stress than is evolved by the same material after it has been blued at a temperature which induces in it a high value of the limit of proportionality. This difference indicates that more work is being done internally by the applied fatigue stress in the work-hardened metal than in the blued material, probably due to greater internal movement of the steel. The evolution of the heat is probably also a definite evidence of internal instability in the steel as worked and of the removal of it by blueing. It may also indicate that in the application of fatigue stress to the worked metal there is more inelastic movement than occurs with the blued material. This is bound to cause a greater heat evolution in the worked material. The same conclusion is indicated by the larger area of the hysteresis loop of the fully worked material as compared with the blued steel. The greater frictional heat and the larger inelastic strain produced within the steel by the fatigue stresses is likely to result in a lower fatigue range of the fully worked steel, and this is actually borne out by the fatigue test results.

The effect upon its limit of proportionality of the application of fatigue stresses to the fully worked material is of great importance. It has been shown that this treatment actually lowers the limit of proportionality of the steel and does not raise it in any way. This can only mean that the application of fatigue stresses has a destructive rather than a healing effect upon the metal. It is to be noted that the highest stress applied in the fatigue stressing was higher than the previous limit of proportionality, and probably higher than the fatigue limit, but also that a similar treatment applied to the quench-hardened alloy steel produces the opposite result—*i.e.*, it raises the value of the limit of proportionality.

The magnetic test results show that there is but little difference in magnetic properties between the fully worked and the blued steel. The change of properties is actually of the same order as was produced in a normalised steel by stressing it to a value approximately equal to its proof stress. This result is to be expected because the steel that is blued is constitutionally similar to the steel as fully worked. It is likely, however, that a state of strain existing within the worked steel will influence the magnetic properties a little. If it be granted that the magnetic properties depend upon the placing of the atoms of the metal into a specific orientation, the freedom of movement or otherwise of the metal as regards the constituent atoms is likely to have some effect. If within the metal a portion of the atoms are constrained and not so free to move as the remainder, these constrained atoms are likely to be less sensitive to rotatory influences, and therefore less likely to take up the best orientation for magnetic purposes. Similarly in demagnetisation a smaller field strength is likely to be necessary to produce a zero flux if some of the atoms have moved out of their initial position to a less degree. Hence the value of the coercivity should be less in a material under strain than in one that is freed from strain. This is precisely what occurs in the tests actually made. It is reasonable, therefore, to imagine that the magnetic test results also indicate the existence of inelastically strained material within the steel as hardened and the absence thereof in the steel after blueing.

All the evidence, therefore, of the tests can be summarised as indicating that the low value of the limit of proportionality in the cold-worked steel is associated with some mechanical instability in the metal that is removed by blueing the steel at comparatively low temperatures, and that this instability is associated with mechanical inelastic straining. It remains, however, to indicate the nature of the instability that is present in the work-hardened metal. The instability cannot be due purely to elastic strain, and it seems very unlikely that it is merely inelastic strain, in the ordinary sense at any rate. A metal that has been subjected to stresses of a magnitude sufficient to produce within it such a measure of distortion as to cause a permanent change of shape has been altered permanently, and when heated it appears not to undergo internal alteration so as to become quite free from inelastic strain until the temperature of the metal is raised to such a value as brings about a structural alteration—*i.e.*, recrystallisation. The instability of a cold-worked steel is just as great in respect of work hardening—which is the reflection of the plastic deformation—after heating to 450° C. as it is before it is heated. The maximum stress, *i.e.*, the "hardness," is not reduced at all by heating to this temperature. However much a cold-worked steel may be heated to those blueing temperatures that produce within it a high value of the limit of proportionality, it will still recrystallise at a temperature of 550° C. or thereabouts. That is to say, it will get rid of the major instability associated with inelastic strain and take up a stable structure. It therefore retains unimpaired this potential capacity for change, which is the reflection or the meaning of instability, even at a temperature of 500° C. This type of instability, therefore, is still in the steel after it has gone through those temperature ranges that produce in it a high value of the limit of proportionality. The low value of the limit of proportionality of the work-hardened metal does not appear, therefore, to be indissolubly associated with the main or major instability of the metal, as this main instability may still exist in the absence of a low value of the limit of proportionality—*i.e.*, in a steel blued at 400° C.

Nevertheless the instability that is represented by the low value of the limit of proportionality is produced in the same operations and at the same time as the major instability just considered. This conclusion follows by the exclusion of all other possible causes. Plastic deformation by cold working has produced the major instability, and has also produced the instability of the low limit of proportionality. The explanation of the latter is therefore likely to be found in an examination of what occurs in the ferrite during the plastic deformation of the metal that is called cold working.

The individual crystals of the steel or, what is probably more accurate, the free ferritic components of these crystals, have been distorted by the working and have been compelled to take up a new external shape. The change of external shape has been produced by slipping and sliding along the gliding planes of the crystals. This action has probably produced along the gliding planes a definite volume of metal in which the atoms of the metal have been torn from their crystalline positions and have been jumbled up so that they form in effect an amorphous layer of material. In such material further slipping may proceed with comparative ease, so long as the movement can proceed along the slip planes already formed. Eventually the gliding will come to an end by some such action as would follow from an increase in the value of the coefficient of sliding friction between the faces of the crystalline metal on either side of the amorphous layer, or by the mutual interference of adjacent crystals in which the slip planes are differently oriented. Also the mere fact of sliding may mean further distortion and hardening which might tend locally to bring the movement to an end.

The atoms of metal in the amorphous layer will always have a tendency to fit themselves once again into the original crystalline atomic distribution. In other words, the atoms of the amorphous metal will constantly tend to "recrystallise" and to pass out of the amorphous state. This is equivalent to a healing of the material ruptures that have occurred on the gliding planes. The healing will probably proceed with extreme slowness at ordinary temperatures, but at elevated temperatures will proceed much more rapidly than at atmospheric. The effect of the healing will be to reduce the ease of slipping along the planes of amorphous material, partly because the quantity of such material will be greatly reduced and the distance between the bounding crystal faces decreased. In all probability, however, complete healing does not occur until a high temperature is reached. There is a remnant of some amorphous metal, and this remains as the rudiment of the slip plane. The constant value of Meyer's exponent up to the stage of total recrystallisation suggests that the slip lines certainly do not heal entirely before that stage is reached.

It may also be considered that the crystalline material is distorted apart from the actual atomic attrition on the faces of slip. This means that the steel retains a certain amount of potential energy, which, at a temperature at which the bonding effect of the amorphous layer becomes sufficiently low, is dissipated by the disintegration of the original crystalline units into a large number of very much smaller ones, the splitting up presumably taking place along the lines that were the original slip planes and in which reside the remnants of the amorphous material that have not assimilated themselves to the surrounding crystalline material.

If this be a true account (as it appears to be from the evidence collected on this point by a number of workers) of the physical action of cold working and the effect of heating, in different intensities, upon cold-worked metal, it fits in perfectly with the experimental evidence that is collected above regarding the material examined. Such an explanation would indicate that the material derived its low value of the limit of proportionality from the ease of slipping along the gliding planes already produced by the previous cold working of the metal, and that the effect of blueing at different temperatures is to bring about a greater and greater degree of healing along these slip planes until the quantity of amorphous metal is reduced to a minimum and the limit of proportionality raised to a maximum, because the opportunity for slip has been so greatly reduced.

The low value of the limit of proportionality in the fully hardened material is the result of the ease with which further slipping may take place upon the pre-existing slip planes in the metal. As these planes are healed by heating, the ease of slipping decreases, and hence the value of the limit of proportionality is raised to the optimum value. When the steel is recrystallised, at the time that the remaining energy in the metal is dissipated, the value of the limit of proportionality falls. In every metallic crystal or collection of crystals the mechanical properties of the collection are influenced by the properties of both the crystalline material and of the surrounding amorphous material. In rough terminology the mechanical properties of the complex are a reflection of the mechanical properties of the weakest part of the complex—*i.e.*, either the crystalline or the amorphous metal. The low limit of proportionality is produced because the amorphous material on the gliding planes permits slipping. When this layer is healed so much that slipping does not occur, the limit of proportionality becomes the measure of the elastic limit of the crystalline material. The maximum value of the limit of proportionality represents nearly the true value of the mechanical properties of the crystalline part of the complex. Naturally the dissipation of the remaining strain energy of the crystalline system at or about 525° C., when the distortion of the crystals disappears, reduces the limit of proportionality or the elastic limit of the crystalline material to the value given by a totally unstrained or undistorted crystal.

The high value of the proof stress, with a low value of the limit of proportionality, is an indication that the actual amount of sliding that takes place along any existing slip plane is not great at any constant stress below the proof stress. This means that although sliding may start it comes to an end, probably by interference between neighbouring crystals. Probably only a few crystals start to slip on the application of a low load. After they have gone a certain distance the adjacent crystals block further slipping, and it is only when the load is increased that new crystals begin to slip. A small amount of movement brings the sliding to an end, and it is only when the stress is high enough to produce new slip planes or to overcome the maximum adhesion on the existing planes that a marked deformation of the steel is produced. This may very well occur at nearly the same stress in all specimens of the same steel that have been blued at temperatures not high enough to reduce the major strain-strength of the crystals.

Although it is not demonstrated in this particular investigation, it is known that the value of the limit of proportionality of a work-hardened material is lower when the amount of deformation by working is greater. The greater distortion produces more slip planes and also is likely to produce a more serious disruption on any one plane. In either event the limit of proportionality of the steel should be lower. If more slip planes are produced, the opportunity for fresh slipping is greater, and sliding is likely to take place therefore at a lower load. Similarly if the layers of amorphous metal are increased in thickness, the ease of slipping is concomitantly increased.

The existence of unhealed slip lines is prima facie evidence of a probability that the fatigue strength will be lower than in the absence of such planes, and it is only by healing the lines that an increased fatigue value will be produced. As the metal has been considerably disrupted along the gliding planes before the actual application of fatigue stresses, it is not very easy to see that the fatigue stresses themselves can give the steel a greater opportunity for healing, and therefore for the raising of the limit of proportionality, in the metal unless such stresses are very small. The fatigue stresses may ease the strain in the crystalline part of the complex, but are hardly likely to heal the wounds produced by the previous slipping. As a result of the relief of strain in the crystalline part, the hysteresis loop may possibly be narrowed. The healing of the lines by blueing will, however, definitely account for the much smaller evolution of frictional heat within the blued steel as compared with that in the fully worked material on the application of fatigue stress.

The solubility of tho steel in acid is likely to be aided by the existence of planes on which slip has occurred, or what is the same thing of a greater amount of amorphous material in the steel. Solution is aided by the juxtaposition of crystalline and amorphous material, and the increased production of layers of amorphous material increases the surfaces of contact between the two kinds of material. The healing of the layers by narrowing them reduces the number of unset atoms, and hence the tendency of the steel to dissolve.

It appears, therefore, that the low value of the limit of proportionality in the cold-worked materials can be explained by the presence in a cold-worked material of planes on which slipping may easily occur, these planes being those on which slipping has taken place during the cold working of the metal. Adhesion of the metal bounding such planes is low. By blueing the steel the disturbances on such planes are healed in a greater or less degree, and the adhesion is increased, until finally it is raised to the same value as the adhesion at the original crystal boundaries. The sliding friction on the slip planes is high, and a small movement of the metal results in a seizing up of the steel on the planes. Consequently, the proof stress is not very markedly lower in the steels with a low limit of proportionality than in those with a high limit of proportionality. The fatigue strength of the steel is rather greater in the steels with a higher limit of proportionality than in those with a low limit of proportionality in which healing has not occurred, because in the former initial failure is easier to achieve.

Attention may now be turned to the alloy steels, and the results of the experimental work considered first. (In order to provide a simple adjectival distinction between these steels and those that have been hardened by cold work, they are referred to herein as "quench-hardened"—*i.e.*, hardened by the suppression of constitutional changes during cooling—as the opposite of work-hardened.) It can be stated at the commencement that all the three alloy steels examined, whether hardened in air or in oil, show the same general features, the variations of properties being of degree and not of kind. The leading fact, of course, is that the fully hardened steel has a low value of the limit of proportionality, which is increased to an optimum value by reheating the steel to a moderately low temperature. The highest value of the limit of proportionality is found in all the steels after they have been reheated to a temperature not less than approximately

400° C. The process of raising the limit of proportionality of this type of steel is accompanied by some fall of the maximum stress of the metal, such as does not occur during the corresponding process of treating the cold-worked steel that has already been considered. The fall of maximum stress is of great importance, as evidence of structural changes that are proceeding within the steel. As with the cold-worked steels the value of the limit of proportionality is rather higher in compression than in tension, and consequently less alteration can be effected in the value of the limit of proportionality in compression by the operation of tempering at a low temperature. Nevertheless, some small increment in the value of this property can be obtained by tempering. In specimens tempered at 400° C. and higher, the limit of proportionality is approximately the same in tension and compression.

The proof stress of the air-hardening steel is by no means so low as might be expected from the value of the limit of proportionality. In fact, the value shown by the steel that is fully hardened is not a great deal lower than that of the same steel after tempering at a temperature that produces the optimum value of the limit of proportionality. In this respect also the alloy steel hardened by "quenching" is very similar to the steel hardened by cold working. There is nothing special or peculiar about the behaviour of the steel with respect to the proof stress.

It is to be noted that the quench-hardened steel when tempered for a long time at a temperature of 100° C. has very much the same properties as are found in the same steel after tempering for quite a short time at a much higher temperature. The value of the limit of proportionality of the steel tempered for a long time is about as high as that of the steel tempered at the optimum temperature. This is brought about without any appreciable diminution of the maximum stress of the steel, and the proof stress value is of course rather higher than that of a specimen tempered at 100° C. for a short time, being in fact approximately that of the steel tempered at the optimum temperature. It is to be assumed, therefore, that temperature is not the sole condition which determines the extent of the alteration of the limit of proportionality, but that time is also of great and perhaps of equal importance in this connection. In this respect the quench-hardened alloy steel differs from the plain carbon steel, work hardened. In the latter steel prolonged heating at 100° C. has not brought about a large alteration in the value of the limit of proportionality. The value has been raised, but not to a value in any way approaching the optimum. It may be, of course, that the time allowed to the cold-worked steel was insufficient. It is to be noted, however, that the alloy steel after tempering for only two days gives nearly the same value for the limit of proportionality as after tempering for a week.

The behaviour of the alloy steels when exposed to the attack of acids shows that the steel undergoes a marked alteration in solubility when heated at different temperatures, the speed of solution rising to a maximum in the specimen that has been tempered at about 300° C. A possible explanation of the observed behaviour has already been suggested along with the report upon the experimental evidence. The whole discussion of these results, in so far as they are of importance in connection with the value of the limit of proportionality of the steel, is complicated by the variety of the changes that may take place within the steel when it is reheated to various temperatures. Many changes may proceed, and some of these certainly do occur, but whether or not they are connected with the value of the limit of proportionality is open to some doubt. The important conclusion to be taken from the solubility tests is that the steel increases in solubility as it is tempered, and that the maximum value of the solubility is attained after tempering at a temperature which produces in the material a high value of the limit of proportionality, but by no means the optimum value. With the cold-worked steel the solubility decreased as the limit of proportionality rose. With the quench-hardened steel the behaviour is rather the reverse. With the cold-worked steel a reasonable connection between the solubility and the limit of proportionality could be indicated. To do this with the quenched steel is more difficult because of the constitutional complexity of the material. Before attempting an explanation the behaviour of the steel in the magnetic experiments must be considered a little.

The effect of reheating the quench-hardened steel is to alter the magnetic properties quite considerably. After heating to 300° C. the steel has acquired values for coercivity and remanence that are much greater than those before reheating. When tempered at 600° C. the change of magnetic properties is still greater. Actually the properties of the metal after tempering at 600° C. are not particularly germane to this inquiry, but they are valuable as an indication of the trend of the influence of reheating upon the magnetic properties. The properties of the steel tempered at 300° C. are, in fact, a step on the path of magnetic change which these steels are following in their passage to a tempering temperature of 600° C. (This has been proved also by various other workers, particularly in U.S.A.) Along with the other changes of magnetic properties produced by tempering there is a marked change in the permeability of the steel.

Now if a sample of the steel is tempered for a week at a temperature of 100° C., the magnetic properties are modified, but not in the same way as by tempering at 300° C. for a comparatively short time. The primary difference is that the permeability is not altered appreciably by the prolonged treatment, and in fact the only change that is produced in the magnetic properties is that the coercivity is greatly affected—just, of course, as the limit of proportionality has already been shown to be altered. The value of the coercivity of the steel that has been tempered at 100° C. for a week is raised to a value that approximates to that of the steel that has been tempered at 300° C. for quite a short time. It is to be remarked that the variations in magnetic properties produced by the prolonged tempering agree very closely with the results of the blueing of the cold-worked steel at a temperature that brings about the optimum value of the limit of proportionality, and that this same prolonged tempering raises the limit of proportionality of the quench-hardened steel to a value that is approximately the maximum attainable.

It is evident. therefore, that the low value of the limit of proportionality in the quench-hardened steel may be altered entirely without appreciably affecting the magnetic properties of the steel apart from the coercivity. Particularly also it is to be noticed that the permeability of the steel with a low value of the limit of proportionality need not be appreciably different from that of the steel with a high value of the limit of proportionality. It is also to be noticed that the value of the permeability of the steel is not appreciably affected if the quench-hardened material is stressed to a value above its optimum value of limit of proportionality, that is in such a way that fresh inelastic strain is introduced into it.

It may reasonably be believed that the permeability of the steel is determined more by its constitution than anything else, and therefore that a constancy of permeability is a reasonable indication of constancy of constitution. (The alteration in coercive force found in the quench-hardened steels is also found in the work-hardened steels when no constitutional change is produced.) If this be so, the magnetic tests indicate that a very high value of the limit of proportionality may be produced without any alteration of the constitution of the steel from that in the quench-hardened state. The result has been established for the cold-worked steel, and certainly seems to be indicated for the quench-hardened steels. It is to be noted also that the magnetic property that most conspicuously varies with the value of the limit of proportionality is the coercivity of the steel. This applies to both the work-hardened and the quench-hardened material.

In order to account for this magnetic behaviour of the steel and the solubility tests upon it, some consideration must be given to the constitution of the quench-hardened metal. It will be admitted generally that the steel contains in its quenched state a mixture of martensite and austenite, in proportions that may be fairly constant or may be quite variable (see Fig. 39, Plate XII.). Neither of these constituents is very stable, particularly under the influence of heat. The austenite when heated tends to pass into martensite with considerable ease, so that the most obvious primary effect of the heating of the steel is the production within it of comparative constitutional homogeneity—*i.e.*, regarding the martensite as a homogeneous material (although in the ultimate analysis it is not). It is also to be observed that austenite is the product of pressure—or of what is the same thing, the prevention of expansion. The transformation of austenite into martensite follows, therefore, from the relief of the confining pressure or by the provision of an opportunity for expansion. Anything, therefore, which tends to assist in these operations tends to produce martensite in the steel, and therefore to produce a homogeneous material.

Martensite, whether formed from austenite directly during quenching or as a result of changes in the steel after the completion of hardening, is in itself a notably unstable substance. Martensite has a great tendency to pass into something more conspicuously heterogeneous, and in fact to revert to troostite. sorbite, and eventually to pearlite. This degradation does not proceed at a measurable rate at ordinary temperatures, but is the firstfruit of an increase in temperature of the steel. The dissolution of the martensite into sorbite or the like is the most generally recognised result of the tempering operation, and is the feature that is usually regarded as represented by the change in the commonly reported mechanical properties—maximum stress, elongation, &c. There are then two constitutional changes going on in the steel during reheating—from austenite to martensite, from martensite to troostite and its products. Depending upon the temperatures of tempering, it may well be argued that the transformation of the austenite really occurs by the direct production of troostite, the formation of martensite being transitory.

The net result, therefore, of heating upon the constitution of the quench-hardened steels—which is really a mixture of austenite and martensite—is to transform the material into a mass of troostite or sorbite or a product intermediate between these two. (The limits of demarcation between the decomposition products of martensite are by no means easy to distinguish, and the distinction appears to be of little importance in the present connection.)

Now the properties of these different constituents vary quite a good deal. The properties of pure austenite are quite well known, as are the properties of sorbite. Whether the properties of pure martensite are known so thoroughly is open to question. The present investigator is not convinced that *pure* martensite has ever been studied, for the very sufficient reason that it may rarely have been produced. At the best it is a transition product between austenite and sorbite, and it is a conspicuously metastable phase. Having entered this caveat, the properties of pure martensite as generally understood may be outlined.

The best-known properties of austenite are, firstly, that it is non-magnetic, being composed essentially of iron in the gamma form. It is also known to be soft and to have a low limit of proportionality. The fact that it is convertible fairly readily into martensite by heating or by stressing has already been referred to. (Throughout the report, of course, it is clear that references to austenite are to the constituent of quenched steels known as austenite—not to the universal solid solution, which is the parent of all the constituents of steels cooled in different ways, in the form in which it exists at high temperatures.)

Martensite, so far as is known of the material in the condition in which it is available for study, is magnetic—its constitutional basis being iron in the alpha condition. Martensite is hard and strong, being in these respects the opposite of austenite. Whether it has a high or a low limit of proportionality remains to be seen. Certainly those materials that are generally regarded as being most definitely martensitic are the materials with the lowest value of the limit of proportionality. But when the material is produced from austenite, as in a 25 per cent. nickel steel, the limit of proportionality is found to be high.

The properties of sorbite, and the other decomposition products of austenite (and martensite) which are so closely related, are simple. The material is magnetic—of a permeability that depends largely upon the mechanical strength of the material. Its strength and hardness depend upon the temperature to which it has been heated, and therefore in general terms to the degree to which the aggregation of the precipitated carbide has proceeded, and hence to the extent to which the carbide and the ferrite have separated from each other. If it be assumed, as is generally the case, that sorbite is the sole residual constituent of tempered steels that have been tempered at a temperature round about 400° C., then sorbite is a material with a high value of the limit of proportionality. It is, in fact, reasonable to say that the highest value of the limit of proportionality comes at the time when sorbite is produced in the steel in the largest quantities. It is also fair to say that in sorbite, when once produced, the ratio of limit of proportionality to maximum stress is very nearly constant, whatever the actual value of the maximum stress.

The regular existence of the high limit of proportionality in sorbite is not, however, to be regarded as leading definitely to the view that the formation of sorbite, in a steel that has been quench hardened, is essential to the production of a high value of the limit of proportionality. It has been shown quite clearly that a high value of the limit of proportionality can be produced in the steel without putting it into the sorbitic state. By tempering at 100° C. for a prolonged period the steel is left in a condition that cannot be described as sorbitic, but it possesses a limit of proportionality which is nearly as high as the optimum attainable. By statically stressing the steel, the limit of proportionality is raised up to a high value, but sorbite is not made thereby. Similarly by fatigue stressing, the same result is attained without producing sorbite. The existence of sorbite, therefore, infers a high value of the limit of proportionality, but its absence does not necessarily preclude the high value, and the presence of a low value is not explained at all satisfactorily by the absence of sorbite.

The existence of austenite within the material might be regarded as providing an explanation of the low limit of proportionality of the quench-hardened metal, in view of the fact that the constituent has itself a low value of limit of proportionality. This, again, is insufficient. If the low value of the limit of proportionality in the quench-hardened steel is due to the low value of the limit of proportionality in austenite, the production of a high value of the limit of proportionality infers the transformation of the austenite into martensite or into a decomposition product thereof. But the transformation of the austenite means the transformation of the gamma iron into alpha iron, and such a change would be reflected in the magnetic permeability of the steel. It has been shown, however, that the limit of proportionality of the steel may be raised—either by prolonged low-temperature tempering or by stressing—to a very high value without bringing about an appreciable change in the permeability of the steel. The low value of the limit of proportionality cannot, therefore, be accounted for by the low value of the limit of proportionality of austenite, *per se*. Similarly austenite can be stressed far beyond its limit of proportionality and given a limit of proportionality three times greater than the normal without producing any noticeable change in the permeability.

The general conclusion, in fact, to be drawn from a consideration of both the magnetic properties of the materials and from the solubility tests is that the low value of the limit of proportionality in these steels is not due to the specific, intrinsic, properties of any one particular constituent, and that the raising of the value is not to be explained by any definite constitutional change that is brought about in the steel by the operation of tempering. As with the cold-worked steel, the explanation must be sought for in the physical or mechanical condition of the quench-hardened steel.

In the consideration of the mechanical condition of the steel, attention must be turned largely to those occurrences that do or may produce abnormal conditions within the steel, or produce or set up states and conditions within the quench-hardened steel that do not apply to that steel in the normal state. The most important thing to search for is any operation that sets up in the metal a state of strain and stress or of instability that would be in itself an abnormality. What are these possibilities ? There is no need to look entirely for strains or stresses, as any physical or mechanical instability is of importance. The particular one that is to become of importance will, however, be one that is removed without any constitutional alteration of the steel, and without causing any marked proportion of the steel to undergo an allotropic change. With these limitations it would seem reasonable to look for strains in the ordinary sense of the term, or at any rate for the product of strains that have been endured and have been relieved.

During the effective quenching of a steel there is a greater or less suppression of expansion. Austenite occupies a smaller volume than its decomposition products, and must therefore expand if it is to undergo a change into any other constituent. If it does not expand, it does not become martensite or sorbite. By pressure it is retained in its true and pristine condition, and by the relief of this pressure it is assisted to pass into martensite. It is not entirely unreasonable to imagine that in a material which contains austenite that is produced by quenching, the austenite is kept in that condition by pressure. This may be external in very rare cases, or more usually may be internal to the steel. The austenite is pressed upon by the surrounding crystals because they are preventing its expansion. The surrounding material, which is presumed to be martensite, is pressing upon the austenite. In all parts, therefore, of the steel there is a mutual stress system, the austenite being compressed and the martensite being stretched. Within the steel, therefore, a very unstable condition appears to exist. All parts of the metal are under stress and are therefore strained. It is quite reasonable, however, to imagine that both in the austenite and the martensite the strain is elastic rather than plastic. When the whole metal is in this state of strain it is not difficult to imagine that further slip may be very easily produced, and hence that the steel will show a low value of the limit of proportionality.

The existence of austenite and the prevention of its expansion will account for the existence of the strain in the metal produced by the stresses set up during quenching. But it does not definitely explain the low value limit of proportionality, nor the raising of the value by tempering. If the mere existence of pressure between the austenite and martensite is the cause of the low value of the limit of proportionality, then it is necessary to reconcile the following facts :

1. That the low limit of proportionality can be removed without any evidence of transformation of austenite into martensite such as would by itself relieve the pressure between the two constituents, *e.g.*, by stressing the metal.

2. That it is possible to raise the limit of proportionality markedly by fatigue stresses without producing any appreciable quantity of heat as would occur if the austenite was bodily changed to martensite—*i.e.*, without doing any large quantity of work. The expansion in the interior of the metal of any proportion of austenite is not likely to occur without the performance of a good deal of work.

3. That if the outside layers of the steel are removed and greater freedom given to the metal the limit of proportionality is raised in the steel.

It is to be noted that austenite is a weaker material than martensite. When pure austenite and pure martensite of the same composition can be examined—*e.g.*, in a 25 per cent. nickel steel—it is known that the elastic limit of the austenite is markedly lower than that of the martensite, and also that the maximum stress is lower than that of the martensite. It is not unreasonable to imagine, therefore, that the stress that comes upon the austenite during quenching, and which must rise to a very high value, does in fact attain a value sufficiently great to exceed the elastic limit of the austenite and to produce within it distortion and slipping of a kind not exceedingly different from that brought about in the cold-worked steel. If this is so, then the presence of the low value of the limit of proportionality in such steel could be accounted for by the propensity for slip of the previously strained austenite. It is not necessary that slipping has been as extensive as in a cold-worked steel, or that so much amorphous metal has been produced. It is not really necessary to assume that the austenite is plastically distorted. The metal may be distorted to the extreme limit elastically, and only a small amount of actual slipping have occurred. It is always possible that the slipping has been partially healed during the final stage of treatment and that only the elastic strain remains. The important point is that the steel is strained and is retained in that strained state.

Such a view is in accordance with the observed behaviour of the metal. The prolonged heating at 100° heals the wounds of strain, and consequently raises the stress at which further slip occurs—*i.e.*, the limit of proportionality. Also the healing gives some opportunity for the relief of the excessive elastic strain on the austenite crystals. The application of fatigue stresses tends towards the same end without necessarily going through the operation of converting austenite into martensite, and therefore without performing a great deal of work. The difference in the effect of the fatigue stresses on the quench-hardened and the work-hardened steels is likely to be due to the difference in the degree to which slipping has occurred in the two materials. The relief of pressure on the austenite when a hardened bar is turned down to small dimensions removes some of the constraint on the material, increases its freedom, and relieves in a measure the strains produced by the internal distortion, and therefore in effect raises the limit of proportionality of the metal. (The fact that similar turning on the work-hardened bar has no appreciable effect upon the limit of proportionality is an indication of the difference in degree in the permanence of the straining of the two types of steel.) The further heating of the steel to higher temperatures completes the healing and also permits—in fact, brings about—the change of the austenite into martensite, thereby reducing the mutual stress between the two constituents. Furthermore, the heating eventually produces a steel consisting of a single constituent—*i.e.*, sorbite (or its allied constituents). By the time that the steel has reached this stage it is as free as it is likely to become from the internal stresses and strains that have been produced in it during quenching. Under these conditions the healing of the metal is likely to become as perfect as is permissible.

If this view of the matter be accepted, the cause of the low limit of proportionality in the two kinds of steel—cold worked and quenched—becomes very similar. There are in fact but very slight differences between the two steels in all the evidence of the effect of the low limit of proportionality upon their behaviour. In view of this similarity of behaviour, it is at least unlikely that there will be any very marked difference in the immediate reason for the occurrence of the low limit of proportionality in the two steels, although the ultimate source of the property is not the same. One of the more definite differences in the behaviour of two steels is the effect of a long exposure to 100° C. With the cold-worked steel the effect of this treatment upon the limit of proportionality is much less than with the quench-hardened steel. This may be due to the fact that in the work-hardened steel the disturbance of the steel has been more violent than with the quenched steel. Also in the latter steel it is at least probable that the strains have not proceeded to the same length in producing actual movement on the slip planes, as has occurred with the work-hardened steel. The distortion of the quench-hardened metal may well contain a high proportion of elastic strain, whereas in the work-hardened metal it is emphatically inelastic. Healing is therefore likely to be easier in the quench-hardened than in the work-hardened metals. The other difference is the effect upon the limit of proportionality of the application of fatigue stresses. The beneficial effect on the quench-hardened steel and the detrimental effect upon the work-hardened may be due to the same difference as that just mentioned.

A point that is worthy of consideration is that the limit of proportionality in compression in both steels is higher than that in tension. This may be connected with the fact that in both steels the stresses that have been applied and that are considered to have produced the phenomenon under examination are compression stresses. The cold-worked steel has been stressed by compression, and it is a compression stress that has been applied to the austenite in the quench-hardened metal. It is generally understood that a metal that has been distorted, or has slipped, in one direction is more easily made to slip in the opposite direction than to slip further in the same direction. Therefore, when a tension stress is applied to the metal that has been compressed, slipping can occur more easily than when a compression stress is applied. This would account for the lower limit of proportionality of the metal in tension than in compression, which is observed in both kinds of steel.

Some consideration ought here to be given to the significance of the low limit of proportionality in the types of steel examined. Throughout this report the term limit of proportionality has been used to the exclusion of the term elastic limit. How far these terms ought to be regarded as interchangeable is entirely a matter of the definition of the elastic limit. The manner in which the value of the limit of proportionality can be altered up or down—by heat treatment or by stress—emphasises more than ever the need for Bauschinger's distinction between the primitive and the true elastic limits. The limit of proportionality is always the primitive elastic limit and should be regarded as such. Nevertheless, under the actual conditions maintaining in the steel at the time of testing, the limit of proportionality *is* the elastic limit or is very near to it. When this stress value has been exceeded the material undergoes some measure of plastic distortion—even though the amount is exceedingly small—and the significance that is to be attached to the primitive elastic limit must be determined by the condition under which the steel is to be employed. In both types of steel it seems fairly evident that the conditions of employment may alter materially the value of the limit of proportionality. Sometimes—in fact generally—the quench-hardened steels will have the value raised. The work-hardened steels, on the other hand, may be often affected adversely by service conditions. In respect of the latter steel it seems to be generally advisable to reheat it before use to such a temperature as will raise the limit of proportionality to its optimum value. This applies particularly to those parts that are to be used in fatigue. Statically loaded parts are, of course, affected by the fact that a certain amount of distortion is produced at low stresses. The proof stress, however, is comparatively unaffected by the low value of the limit of proportionality, a fact which indicates the small amount of distortion that actually occurs on stressing to values below the proof stress. The importance, therefore, of the low limit of proportionality in statically loaded parts depends entirely upon the seriousness of the effect of the small permanent deformation produced at stresses below the proof stress. It seems likely that in the majority of engineering instances this degree of distortion will scarcely be of importance.

In the quench-hardened steels the attainment of the optimum value of the limit of proportionality is always accompanied by a drop in maximum stress, and at times the drop is sufficiently great to render the part so treated unsuitable to perform the duties expected of it. An example of such a case is found in air-hardened or oil-hardened nickel-chromium steel gears. Fortunately, however, in the quench-hardened steels, exposure to reasonable fatigue stresses has the effect of raising the limit of proportionality and bringing it nearer to the true elastic limit of Bauschinger. In this way the steel is rapidly rectified from the evil effects of quenching. It is extremely rare for steels in the 100-ton condition to be employed in statically loaded positions. Where, however, they are so used it would seem best for a fairly prolonged tempering at a temperature of about 150° to 200° C. to be given to the parts before they are put into service. Four hours at this temperature is quite a good treatment to apply and will not bring about any serious drop in maximum stress.

Finally, the results given above indicate the utter futility of the quotation of values for the yield point of such steels as are dealt with herein. The yield point is quoted in specifications prepared by private firms and also in those drawn up by public bodies. For such steels as are considered in this report the yield point is not only meaningless but the quotation of its presumed value may be positively misleading. Through a slackness of expression that has endured for many years the yield point has been given an interpretation that it will not bear, and the meaning that can be attached to the yield point when referring to normalised mild steels has been transferred to other steels—such as those reported on here. This practice is quite unjustifiable. In the first place these steels have no yield point, properly so called. Secondly, the value that is often termed the yield point —*i.e.*, the indeterminate point obtained by the drop of the beam of the testing machine—is quite indefinite and is only vaguely related to anything fundamental in the material. As a basis for stress calculations where the yield point is tacitly assumed to be the general equivalent of the elastic limit, the yield point, so called, is extremely misleading. Many steels having a limit of proportionality of 20 tons or thereabouts are reported as having a yield point of 90 tons per square inch. Under the best conditions of tempering the elastic limit of such steel does not rise beyond about 70 tons.

It can be admitted at once that the limit of proportionality is a property that easily varies in value and furthermore is a property that is difficult to measure. The substitution of the limit of proportionality for the yield point would therefore probably be of doubtful advantage. Such objections do not apply to the proof stress. This property is at least definite in its interpretation and is fairly constant and is not at all difficult to measure. There would seem, therefore, to be solid advantages in calling for this value in the specifications for most steels, other than mild normalised steels, in preference to quoting the non-existent yield point. Actually, it seems to be a little unnecessary for general engineering purposes—as opposed to such special cases as arise in, say, aircraft structures—to quote either the yield point or the proof stress in specifications for such steels as are at present under consideration—whether they are fully hardened or reheated. There is sufficient evidence now available to establish that the regularity of the ratio between maximum stress and proof stress or between maximum stress and fatigue range is quite as constant as need be desired. (This refers to any one steel in any one condition and does not mean that the ratios are constant between different steels differently treated.) A knowledge of the maximum stress together with a definite knowledge of the treatment that has been given to the steel is now really sufficient for general purposes to establish the value of those other properties that the engineer may feel disposed to employ in his calculations.

Iron and Steel Institute.

IRON IN ANTIQUITY.[1]

By J. NEWTON FRIEND, D.Sc., Ph.D., F.I.C. (Birmingham).

There is a peculiar fascination in tracing the history of men and things through bygone ages. The more educated we become the greater is our desire to learn about our progenitors, how they lived and what manner of men they were. It is but a century ago that practically nothing was known about former ages other than that recorded by ancient writers. Indeed, Dr. Johnson is reported [2] to have said that "All that is really *known* of the ancient state of Britain is contained in a few pages. We *can* know no more than what the old writers have told us."

Partly as the result of religious conservatism, which limited the age of the earth to a mere 6000 years and naturally regarded man as even younger, there seemed but little encouragement or scope for antiquarian research. The attention of scientists was therefore in the main directed into other channels. Fortunately, however, both the astronomer and the geologist came eventually to realise that 6000 years are but as a day in the history of the universe in general and of the world in particular. They suggested provisionally a minimum of about 100 million years for our solar system. Although this may yet prove to be far too short a time, once these views became accepted, the antiquary could claim a longer lease of life for man, and there was thus opened out before him an enormous field for research fraught with possibilities hitherto undreamed of. No longer was man's antiquity limited to 6000 years minus six days; his history might conceivably extend through a period of several hundred thousand years.

Although it is now generally conceded that man has ascended from the lower animals, there is considerable diversity of opinion as to the time when the branching off took place. Whilst Gregory[1] places it in post-mid-miocene times, which would make it, according to his computation, close upon one million years ago, Keith[2] considers it must have happened in pre-miocene times, that is appreciably longer still. In either case the field is sufficiently large to keep the antiquary busy!

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[1] This monograph is not a report of work done in respect of a grant from the Carnegie Research Fund. It represents the results of several years' patient research into historical records by Dr. Newton Friend. On its completion he generously offered it to the Iron and Steel Institute for publication, and by order of the Council it has now been included in the present volume of the *Carnegie Scholarship Memoirs.*

[2] Boswell, "Life of Samuel Johnson," chapter xl.

Obviously in those far-off days there was no written word, as we understand it. All hope of finding contemporary manuscripts is thus out of the question, for these could only be produced after man, through unrecorded ages of toil, had progressed upwards to a relatively high state of civilisation. Nevertheless, several methods are open to us by which glimpses can be obtained of the way in which primitive man lived.

1. First there is the application of pure reason or philosophy to the problem. This was the accepted method of the Greeks, and is beautifully exemplified by the writings of Lucretius[3] *circa* 56 B.C., to which further reference is made later.

2. It may so happen that the foregoing method is, in certain cases, the only one by which pictures of the past can be obtained. It was practically the only avenue open to Lucretius, yet later researches have tended to show that his conjectures are surprisingly near the mark. In many cases, however, philosophy may be supplemented, checked, and corrected by a study of modern savage life, or of records chronicled by observant travellers in uncivilised lands. This is abundantly illustrated in the sequel.

3. By far the most beautiful and conclusive evidence is, however, to be found in the earth itself. Around us and beneath us lie traces of man's handiwork in such various forms as implements, paintings, carvings, and the like. These the antiquary skilfully pieces together, and every year sees, unfolded to our wondering eyes, some new detail in the fascinating story of man's childhood.

It is one of those pleasing ironies with which the history of science abounds that, at the very time when Dr. Johnson declared the impossibility of learning more about primitive man, "there was lying in the Sloane Museum a rudely-chipped flint weapon which had been found, at the end of the seventeenth century, associated with an elephant's tooth, 'opposite to black Mary's near Grayes inn lane,' in which street once lived Johnson."[1] The language was there, but the interpreter was wanting.

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[1] W. K. Gregory, "The Origin and Evolution of the Human Dentition" (Baltimore, 1922).

[2] A. Keith, *Nature*, 1922, vol. cx. p. 835.

[3] Lucretius, *De*]*Rerum Natura*, translated by Munro (Routledge). Lucretius died about 52 or 51 B.C.

By dint of persistent application of the foregoing methods of study the antiquary has been able to portray, with an astonishing wealth of detail, the story of the life of our primitive ancestry. Only the briefest sketch of this can be attempted in these pages.

The Age of Stone.

In those far-off times when man was hardly to be differentiated from the brute creation his weapons would be natural objects just as nature formed them; the trees, the forests, and the caves would form his home. As Lucretius[2] says, when speaking of primeval man, "Arms of old were hands, nails and teeth, and stones and boughs broken off from the forests. . . . Trusting to the marvellous powers of their hands and feet they would pursue the forest-haunting races of wild beasts with showers of stones and clubs of ponderous weight; and many they would conquer, a few they would avoid in hiding places."

Bitter experience would gradually teach them to prepare beforehand their weapons and keep them in readiness for all emergencies, just as David, prior to his encounter with Goliath hundreds of thousands of years later,[3] "chose him five smooth stones out of the brook, and put them in the shepherd's bag which he had, even in his scrip."

At first the weapons of primitive man would be extremely crude; so rough and shapeless that the modern antiquary may well doubt if they have ever been used by human hands. Such stones are termed *eoliths*, from the Greek *eos*, dawn, and *lithos*, stone. But it would soon be observed that, other things equal, the most successful hunter and warrior was he who had the finest weapons. Increasing attention would therefore be paid to the shaping of the implements, which would now begin to bear such obvious signs of skilled workmanship that no longer is the antiquary in doubt as to their human origin. They are known as *paleoliths,* from the Greek *palaios,* ancient, and are usually of flint, which is particularly amenable to chipping, although other stones were sometimes used. The coarse, rude flaking of the earlier specimens was gradually improved upon, and ultimately tools and weapons were produced exhibiting exquisite workmanship. These are known as *neoliths,* from the Greek *neos,* new. Some of the very finest specimens have been found in Egypt and date back to a little before the First Dynasty—that is *circa* 4400 B.C. The cutting edges have been produced by such fine chipping, involving thousands of minute flakings, that at first glance they appear to have been ground perfectly straight like a modern knife edge. It is not until they are more closely examined that their true serrated nature is apparent. Such implements must have taken a very long time to make and, being too valuable for ordinary use, were probably reserved for religious ceremonial, just as, at the present day, choice tapestry and needlework are consecrated to the churches. According to King and Hall [1] the Egyptian specimens referred to are "undoubtedly the most remarkable stone weapons ever made in the world."

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[1] Clodd, "The Story of Primitive Man" (Newnes, 1897), pp. 9–10.

[2] Lucretius, *op. cit.*, Book V.

[3] 1 Sam. xvii. 40, R.V.

Flint was not the only material used by neolithic man; implements in other stones such as quartzite and even in minerals such as Cumberland red hæmatite or Kidney ore have been found. Nor were the implements always chipped. Frequently they were ground to a smooth cutting edge. Some of the knives were curved like a pruning hook or sabre, whilst the winged arrows and spear-heads were produced with magnificent symmetry.

The most common form of neolithic implement is the axe-head, or *celt*—a word possibly derived from the Latin *celtis,* chisel. They were known to both Greeks and Romans as "thunderbolts"; the Germans and Scandinavians term them "Thor's Hammers." In Britain and Ireland many country folk look upon flint arrow-heads as weapons shot by elves, whence the name *elf-stone,* or *elf-shot.* Mounted in silver, they are a sure safeguard against poison and the evil eye.[2]

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[1] King and Hall, "Egypt and Western Asia in the Light of Recent Discoveries" (S.P.C.K.), 1907, p. 14.

[2] Clodd, *op. cit.,* p. 99.

NATIVE METALS.

The question naturally arises as to whether or not primitive man ever made use of native metals. There is every reason to believe that he did. This does not mean that he necessarily realised the connection between the metals and the ores around him. Rather would he regard the metal as a particularly useful kind of stone. He would be struck by the fact that the " stone " did not chip or crack upon being hammered ; on the contrary, it would yield to the strokes and could be cold worked into simple shapes. Possessed of great tenacity, and yielding a fine hard edge when rubbed or ground, some of his most valued implements would be made of metal. On account of its comparative rarity and unique properties, he would be inclined to receive it as a gift from the gods and ascribe to it divine powers.[1]

We are led to these conclusions from a study of savage life within historic times. To quote a familiar example, within the environs of Lake Superior, in the U.S.A., large masses of native copper occur, and there have here been unearthed at various times numerous axes, lance-heads, and other primitive implements composed of this metal, all shaped by hammering. The Indians of the North Pacific Coast had learned to utilise the deposits of native copper in the Chilcat country, north of Sitka, on the isle of Baranof, and the copper shields made by them travelled down the coast to Queen Charlotte's Island.[2]

But if native copper was used by primitive man, does it necessarily follow that native iron was also utilised by him? Upon this point there has been a conflict of opinion. It is generally accepted that the bulk of native iron is meteoric and not telluric in origin. Some have urged that the amount of this meteoric iron is so small,[3] and the chance that primitive man would come across it is so remote, that it may be left out of consideration. Zimmer,[4] however, in a masterly analysis of the subject, has finally disposed of that idea. He shows that a minimum of 246 tons of meteoric iron is known to science at the present time, and in prehistoric times there were all the accumulations of previous ages for primitive man to draw upon. Hence it is reasonable to suppose that meteoric iron must have been considerably more abundant than now, particularly when it is remembered that, in consequence of its nickel content, celestial iron has a much longer life than telluric iron, because of its enhanced resistance to corrosion. Further, as Zimmer points out, "it is certainly a fact that fewer iron meteorites are found in the Old World than in the New, which is an argument in favour of the use of meteoric iron by primitive people. The Old World having as a whole the older civilisation, the meteoric iron was used up by the ancients, while in the New World it has accumulated and is now being found." Indeed, "it is not to be wondered that the meteorites are more frequently found in America, for those which have fallen in the Eastern Hemisphere have been turned to some uses, often fantastic, centuries ago. They have been forged into weapons with magical attributes, set up as idols, pounded for medicine, and worn as amulets." [1]

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[1] This idea receives support from the attitude of semi-civilised peoples towards metals within historic times. An apt example is afforded by the superstitious reverence accorded to Gunnar's famous bill (or battle-axe) in the Icelandic saga times (see p. 253.)

[2] Ridgeway, " The Early Age of Greece " (Clay & Sons), 1901, vol. i. p. 595.

[3] See Gowland, " Huxley Memorial Lecture for 1912," Royal Anthropological Institute of Great Britain and Ireland.

[4] Zimmer, *Journal of the Iron and Steel Institute*, 1916, No. II. p. 306.

Again, the view has been taken that meteoric iron is too brittle to be cold-worked in primitive fashion. This implies that only the telluric metal was available to man prior to the iron age, and, as has been mentioned, the supplies of native telluric iron are in general exceedingly small. Petrie [2] has fallen into this error; nevertheless he agrees that long before iron was recognised as a metal, at any rate in so far as the Egyptians were concerned, implements of this material were not unknown. He assumes that the metal had been found native, or else produced casually by accident. Meteoric iron, however, is not usually brittle.[3] Zimmer estimates that only 1 per cent. of the meteoric metal known to science is brittle, leaving 99 per cent. available to man for cold working.

This much is clear, therefore. There was sufficient malleable meteoric iron on the earth to supply primitive man with an appreciable number of implements. The question now arises as to whether or not primitive man was sufficiently intelligent to make use of it. The answer to this is probably in the affirmative. Many of the large meteorites are of such irregular shape that it would not be impossible for primitive peoples, even with flint tools, to sever some of the protuberances. The Otumpa meteorite (Argentine), the original weight of which was probably about 15,000 kilogrammes, shows no fewer than six places from which portions have been removed. The Descubridora meteorite (Mexico), which weighed about 575 kilogrammes, has a gap 9 centimetres long in which is wedged a broken copper chisel left by some primitive workman.

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[1] A. Harvey. Quoted by Zimmer, *loc. cit.*, p. 348.

[2] Petrie, "Ancient Egypt," 1915, Part I. p. 12.

[3] Gowland, *loc. cit.*, p. 277.

"Meteoric iron was cut by the ancients in the same way as they cut pieces off the large masses of native copper found on the banks of Lake Superior. A block of such copper which was found in 1875 on the territory of the Minong Mining Company (Isle royale, Lake Superior) 16 feet 6 inches below the ground in ancient workings and which weighed 5720 lb., showed definitely the marks of primitive tools where portions have been severed. A piece which had been so detached in antiquity has been found in Ohio, hundreds of miles from the main mass. A similar mass of copper in the Minnesota mine, near the Ontonagon River, also in ancient workings and 18 feet below the surface, weighing 6 tons, had been nibbled all round by the Stone Age man.

"It is of course not suggested that iron can be cut as readily as copper, but the following incident, showing how primitive man, with the simplest tools and patience, can cut up heavy masses of iron, happened in 1727 after Roggeween had lost one of his ships on one of the South Sea Islands. The natives collected all the iron from the wreck eagerly, lifted the anchors from the sea in the harbour of Tahiti, cut them up, and the King of Tahiti sent a piece of one of the anchors as a rare present to the King Opuni of Borabora." [1]

Again, as regards small meteorites, or tiny pieces of native metal of telluric origin, these might be worked up as beads or other ornaments. Probably this was the origin of the metal beads, the oxidised remains of which have been found in predynastic tombs in Egypt, dating back, in all probability, some 6000 to 7000 B.C.[2]

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[1] Zimmer, *loc. cit.*, pp. 337–8.

[2] See p. 277.

A study of primitive life within historic times is here, however, of considerable help. Numerous records are extant of travellers who have found rude peoples using iron implements which they could not have obtained either by barter or by metallurgy. According to Zimmer,[1] when in 1721 Hans Egede found the Eskimos using arrows, spears, &c., with bone and stone points, he also found them occasionally tipped with iron points. Hearne[2] in 1772 visited an Eskimo tribe on the Coppermine River and observed that whilst they were as a general rule using weapons and implements of native copper, they also possessed a few which were evidently of meteoric iron. He described two pieces, one 1⅜ inch by 3½ inches, converted into a knife as used by a woman, and the other, 1 inch by 2⅜ inches, which was mounted on a piece of walrus tusk and used as a man's knife. Further, Sabine, who accompanied Ross in 1818, reported that the Eskimos of Cape York in Baffin Bay, on the west coast of Greenland, employed meteoric iron in a similar manner, the members of the expedition being particularly attracted by the knives they used. He stated that every one of the Eskimos who visited them on and after August 10, 1818, carried an implement with an iron edge which served as a knife. The handle was from 9 to 11 inches long, being made of flat bone, whilst the cutting edge was formed by a series of from three to seven flattened flakes of iron inserted into a groove in this bone, extending to about half its length. "It transpired that the source of the iron was the three masses of the Melville Bay meteorite, and that the pieces detached were beaten flat between stones without heat. One of the masses, known as 'The Woman,' was softer than the other two, and was, therefore, almost exclusively used. It is estimated that nearly one-half of the original mass has been detached by the Eskimos through many generations, about 12 cubic feet being left."

From the foregoing the assumption appears by no means unreasonable that primitive man, even when still in the stone age, could and did make use of native iron, whether meteoric or telluric, in fashioning some of his most valued tools and weapons. If that is the case, why are iron tools not found in stone age burials? The obvious explanation is that the metal would quickly rust and all trace of it would rapidly disappear. As is so often the case, however, further consideration shows that "the obvious" cannot be correct. Petrie [1] is undoubtedly near the truth when he says, "The supposition often put forward that iron might entirely disappear in course of time, is a mere fallacy. When buried in earth iron rusts much more slowly than if exposed to air, and in many situations it is remarkably preserved. When it has at last been turned to rust, it has become a material which can never disappear.[2] A lump of oxide of iron is practically insoluble when buried, and its strong colour and staining power make it very obvious. To remove all trace of it when buried would be impossible within the human period by any conditions." Although this last sentence appears to the present writer somewhat too liberal, in the main the foregoing argument is undoubtedly correct.

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[1] Zimmer, *loc. cit.*, p. 308.

[2] Hearne, *Reisen nach dem nördlichen Weltmeer*, 1797, p. 118.

Zimmer [3] suggests that the iron implements "were much too valuable to be buried with the dead, and not likely to be left behind by careless owners"—hence their scarcity in museums. This is borne out by modern savage life. Livingstone [4] mentions an interesting case of a native of the central regions of Southern Africa whom he met during his travels. The man had a bow about 6 feet long and iron-headed arrows about 30 inches in length. These he prized greatly, for he had a store of wooden arrows also, neatly barbed, to shoot in cases where he might not be quite certain of recovering them.

THE AGE OF METALS.

Although, as has been shown, there is every reason to believe that primeval man was, in certain districts, more or less familiar with one or two of the more common native metals, he was still struggling in the throes of what the antiquary has termed the stone age. It was not until he had learned to prepare metals direct from their ores that he passed into the so-called "age of metals."

The precise manner of the discovery of metals is, of course, unknown. Possibly a lump of ore had by chance been one of a ring of stones surrounding the camp fire, and becoming embedded in the embers was more or less reduced to the free metal.[1] Possibly, as Lucretius said, "fire had burnt up vast forests on the large mountains, either by a discharge of heaven's lightning, or else because men waging with one another a forest war had carried fire among the enemy to strike terror, or because drawn on by the goodness of the soil they would wish to clear rich fields and bring the country into pasture, or else to destroy wild beasts and enrich themselves with the booty. . . . Whatever the fact is, from whatever cause the heat of flame had swallowed up the forests with a frightful crackling from their very roots and had thoroughly baked the earth with fire, there would run from the boiling veins and collect into the hollows of the ground a stream of silver and gold, as well as of copper and lead. And when they saw these afterwards cool into lumps and glitter on the earth with a brilliant gleam, they would lift them up attracted by the bright and polished lustre, and they would see them to be moulded in a shape the same as the outline of the cavities in which each lay." Thus would be aroused the curiosity and interest of primeval man, and his attempts to convert the metals into implements would render him familiar with many of their peculiar properties.

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[1] Petrie, "Ancient Egypt," 1915, Part I. p. 20.

[2] Ordinary conditions are of course assumed.—J. N. F.

[3] Zimmer, *loc. cit.*, p. 306.

[4] Livingstone, "Missionary Travels" (Ward, Lock), p. 235.

What the particular metal or mixture of metals discovered in this way might be depended upon circumstances. Usually copper, or an alloy of this metal with tin, antimony, arsenic or nickel, was produced according to the nature of the ore employed. Thus, in Hungary, where the copper ores are associated with those of antimony, the early implements consist of an alloy of copper containing up to 4·5 per cent. of antimony. Similarly implements from Egypt sometimes contain 4 per cent. of arsenic, whilst those from Germany have from 2 to 4 per cent. of nickel.[2] In Cornwall, where copper and tin ores are found together, the earliest metal implements consist of what may be termed a "natural bronze." In Ireland, on the other hand, owing to the fact that neither ores of tin nor those of copper containing tin were discovered in early times, the first Irish metallic implements were made of a more or less impure copper.

Although this stage of culture is usually designated as the

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[1] This is Gowland's view, "Huxley Memorial Lecture for 1912," Royal Anthropological Institute, p. 237.

[2] Gowland, *loc. cit.*, p. 240.

" copper " or " bronze " age, according to circumstances, it must not be supposed that copper or its alloys constituted the only metal known. There is abundant evidence that, in different districts, silver, lead, gold, and tin have been known from very early times. One example will suffice. Within the ruins of the second ancient city of Troy, which Schliemann erroneously concluded to be the Homeric city, but which is now known to have been many centuries older and probably dates back to *circa* 2200 B.C., numerous interesting metallic remains were found. These comprised considerable treasure of gold and silver vessels. ornaments of the same, together with weapons of copper and a hideous idol of metallic lead, evidently representing some ancient goddess.[1]

The discovery that bronze is not obtained from a single ore but from a mixture of at least two ores represents a relatively high degree of metallurgical knowledge, and would soon be followed, if indeed it had not already been preceded, by the discovery of iron in such districts as possessed ores of that metal near to the surface of the soil. Once the greater strength of this latter metal was appreciated, copper and bronze would be relegated to a second position and implements of iron would be employed where hardness and tenacity were essential. Lucretius waxes eloquent in describing this transitional period. " With copper," says he, " they would belabour the soil of the earth, with copper stir up the billows of war and deal about wide gaping wounds and seize cattle and lands ; for everything defenceless and unarmed would readily yield to them with arms in hand. Then by slow steps the sword of iron gained ground and the make of the copper sickle became a byword ; and with iron they began to plough through the earth's soil and the struggles of wavering war were rendered equal."

But the development of man has not proceeded along identical lines all over the world. Whilst in many cases a copper or bronze age has succeeded the age of stone, in some countries man has passed direct from stone to iron. Such was the case, for example, in Southern India,[2] in Australia, New Guinea, and with the inhabitants of the Pacific Islands. In most cases this is probably due to the advent of traders who have brought the iron from more highly civilised countries. There is reason to believe that "the negroes of Africa have had no copper or bronze age, but passed at once into that of iron, because they learned the art of working in iron from Egypt before they knew of any other metal except gold."[1] In Egypt the iron age was preceded both by a bronze age[2] and a copper age.

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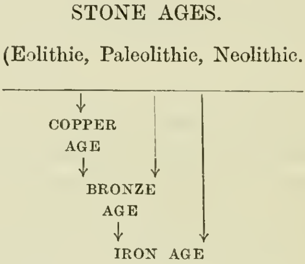
[1] Cotterill, " Ancient Greece " (Harrap & Co.), 1913.

[2] Vincent A. Smith, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 183. See also p. 272.

Man's upward path may therefore be given diagrammatically as follows :



These different ages, as they are conveniently termed, do not constitute definite time limits ; rather do they represent stages of civilisation or culture. It is important to bear this in mind, particularly when inquiring as to how long iron, whether telluric, meteoric or manufactured, has been used by man ; for just as the nations to-day differ in the relative degrees of their civilisations, so in past ages like differences occurred. Some of the peoples were living in their stone age, whilst others employed weapons and tools of bronze, and yet others had become familiar with iron. For example, the inhabitants of Britain were using stone implements at a time when Assyria, Egypt, Greece, and also China, were well acquainted with iron. Again the inhabitants of Thessaly continued to use their stone weapons and their peculiar native pottery long after the culture of the bronze age had penetrated into Crete and Southern Greece. They continued to use them, indeed, until the Cretan bronze age had passed its zenith and the time for the introduction of iron had all but arrived.[1]

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[1] Ridgeway, "The Early Age of Greece" (Cambridge University Press), 1901, vol. i. p. 599.

[2] Gowland, *loc. cit.* See also p. 278.

Similar variation in culture frequently occurred in one and the same small country. We learn from Roman sources that in 55 B.C., the occasion of the first visit of Julius Cæsar to our shores, the Brigantes in the North were still using weapons of stone, whilst the more cultured inhabitants of the South were familiar with both bronze and iron.[2]

Transition Periods.

The existence of a hard and fast line of demarcation between the different "ages" mentioned above is not to be expected. Not only does the human mind take time to absorb new ideas, but for many obvious reasons a metal could not be expected to supplant immediately and completely its predecessor. It need occasion no wonder, therefore, that in certain prehistoric remains, notably those at Hallstadt in the Austrian Tyrol, implements of iron and of bronze have been discovered, lying side by side, indicative of contemporary employment. An interesting example in our own country is afforded by a dagger found in the river Witham.[3] The lower part of its sheath, which is of bronze, is slightly decorated in regular late Celtic style—which fixes its period. The hilt, again, is of bronze, but the blade is of iron, illustrating the overlapping of the two metals.

In Egypt, the use of copper can be traced back to shortly before the First Dynasty, *circa* 4400 B.C. Yet stone weapons and implements were in common use down to the Second or Third Dynasty. During many centuries, therefore, copper and stone implements were used side by side, this transition period being termed the "chalcolithic age" (Greek χαλκος, copper). Stone implements were even in use till the close of the Twelfth Dynasty, *circa* 2000 B.C., so that, strictly speaking, the transition age extended to this later date.

Again, iron was known in Egypt even in pre-dynastic times, some 6000 to 7000 B.C.,[4] although it was not in common use until about 1300 B.C., and during the later part of this period it was gradually supplanting copper and bronze.[1]

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[1] Hall, "Aegean Archæology" (Warner, 1915).

[2] See pp. 238, 241.

[3] Clinch, "Handbook of English Antiquities" (Gill, 1905).

[4] Petrie, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 182.

In addition to these true periods of transition between the ages of stone, bronze, and iron, during which the various peoples concerned are gradually being educated to more advanced stages of culture, there are what may be termed *artificial* or *false* periods of transition during which relics of some ancient customs survive long after the age to which they belong has passed away. This may be due to a variety of causes. The temporary force of local circumstances may effect a recrudescence to simpler forms of life, as, for example, when owing to shortage of weapons some of the Saxon troops under Harold at the Battle of Hastings were armed with stone hammers.[2] An interesting modern example is afforded by Austria, into which country iron coins were introduced soon after the great European war had begun. This was owing to the shortage of copper or nickel; Italy followed suit towards the close of the war, whilst Belgium employed zinc.

Religious and personal conservatism each play an important part in national progress. Thus we read that the command went forth to Joshua,[3] " Make thee knives of flint, and circumcise again the children of Israel." This was done, although bronze knives would have been equally efficient, but the use of metal would have been irreverent. Similarly the stone altars of our churches to-day are interesting historical links with those used by early man when worshipping his gods under the blue arch of heaven—as witness the remains at Stonehenge and elsewhere. The command is still obeyed in our Established Church[4] : " And there shalt thou build an altar unto the Lord thy God, an altar of stones : thou shalt not lift up any iron tool upon them."

The same veneration came later to be manifested for bronze, iron being regarded with suspicion. Thus, it was an ancient custom to mark out the site of a new town with a bronze ploughshare ;[5] and the priest of Jupiter in ancient Rome was permitted to shave only with a bronze razor.[5] The same idea lies at the root of the fear with which smiths and workers in iron were regarded. Thus Vulcan is endowed with supernatural powers and takes his seat amongst the gods. In the caverns beneath Etna the Cyclopes forged the armour for Achilles ; and so on.

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[1] The bronze age in Egypt, as distinct from the chalcolithic or copper age, was apparently entered upon only a short time before the iron age.

[2] Clodd, *op. cit.*

[3] Joshua v. 2, R.V.

[4] Deut. xxvii. 5.

[5] See R. A. Smith, " A Guide to the Antiquities of the Bronze Age " (British Museum, 1920), p. 7.

Herodotus,[1] writing about the year 450 B.C., furnishes us with an excellent example of the survival of the stone age in his day in connection with the Egyptian habit of embalming their dead. Describing the most expensive process, as carried out for wealthy people, he says : " They take first a crooked piece of *iron*,[2] and with it draw out the brain through the nostrils, thus getting rid of a portion, while the skull is cleared of the rest by rinsing with drugs ; next they make a cut along the flank with *a sharp Ethiopian stone*, and take out the whole contents of the abdomen, which they then cleanse, washing it thoroughly with palm wine, and again frequently with an infusion of pounded aromatics. After this they fill the cavity with the purest bruised myrrh, with cassia, and every other sort of spicery except frankincense, and sew up the opening. Then the body is placed in natrum for seventy days, and covered entirely over. After the expiration of that space of time, which must not be exceeded, the body is washed, and wrapped round, from head to foot, with bandages of fine linen cloth, smeared over with gum, which is used generally by the Egyptians in the place of glue, and in this state it is given back to the relatives, who enclose it in a wooden case which they have had made for the purpose, shaped into the figure of a man."

In so far as his statements can now be checked by archæological investigation, Herodotus appears to have been a very careful and accurate observer. It is highly probable that he himself witnessed the different processes of embalming being carried out, for a little later in his work (namely, in Chapter 99) he distinctly says : " Thus far I have spoken of Egypt from my own observation, relating what I myself saw, the ideas that I formed, and the results of my own researches."

An examination of existing mummies quite confirms the assertion that the brain was extracted through the nostrils, and it is evident that, however skilfully such was done, it would still be desirable to rinse out the skull "with drugs." The most interesting feature of the process, however, from the present point of view, is the statement that whilst a metal tool was employed for clearing the head, a stone knife was used for cutting the abdomen.

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[1] See "The History of Herodotus," translated by Rawlinson, Book ii., Chapter 86.

[2] Italicised by the present author.

Now at the time that Herodotus wrote, namely *circa* 450 B.C., the Egyptians had been familiar with copper for about four thousand years, and even iron had been well known and used for many centuries. After the Twelfth Dynasty, that is *circa* 2000 B.C., implements of stone had ceased to be in ordinary use, so that the embalming knife was a survival of very ancient times.

A curious example of the survival of stone age culture in Egypt within recent years, as the result of personal conservatism, is afforded by Mariette[1] and by Maspero,[2] both of whom were acquainted with a Copt in charge of the archæological excavations at Abydos. This man continued to shave his head, throughout his life, with a flint knife. He died when over eighty years of age in 1887 and was still faithful to his flint razor, despite the fact that his sons and the whole population of El Kharbeh were using nothing but steel razors. "As his scalp was scraped nearly raw by the operation, he used to cover his head with fresh leaves to cool the inflamed skin!"

Iron and the Language.

It is necessary to be very careful when attempting to connect the history of a substance, particularly of one which dates back into remote antiquity, with language. Words frequently undergo striking changes in meaning, which may easily lead the inquirer astray. For example, vermilion was originally known as *minium*, but owing to frequent and excessive adulteration with red lead, the term gradually passed from vermilion to its adulterant. In tracing the early history of the pigment, therefore, this point must be borne in mind. A more recent illustration is that of the washerwoman's "copper," which, though now made of iron, retains its old appellation. Conversely "fire-irons" are frequently made of brass.

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[1] Mariette, *Bull. Institut égyptien*, 1869–1871, 1st Series, vol. xi. p. 58.

[2] Maspero, "The Dawn of Civilisation—Egypt and Chaldea." Translated by McClure. (S.P.C.K., 1910.)

The Mexicans called their own copper or bronze "tepuztli," a word that is said to have meant originally "hatchet." The same word is now used for iron, with which metal the Mexicans were already familiar at the time of the Spanish Conquest. Tepuztli then became a general name for metal, and when it was necessary to distinguish copper from iron, the former was termed *red* and the latter *black tepuztli.*[1] From this it would appear that the Mexican language was spoken before iron was known by the people themselves. Max Müller adduces reasons for supposing that iron was not known previous to the separation of Aryan nations, since the names for it vary in the different languages.[2] The Sanskrit word *ayas* referred originally to copper or "the metal." Later on it came to mean iron. Similarly Greek was spoken before iron was known. The Greek word *chalkós* at first referred to copper, but later came to mean iron as the latter metal gradually supplanted the former, whilst *chalkeus,* originally a copper smith, is used in the *Odyssey*[3] to designate a worker in iron. Later on, however, the Greeks used the word *sidēros* for iron. This would appear to be connected with *sidus,* a star, and is usually regarded as indicating that meteoric iron was known.

The Latin *aes,* and the Gothic *aiz,* both derived from the Sanskrit *ayas,* meant copper or bronze. The Romans were accustomed to use qualifying adjectives in conjunction with *aes* to designate the particular type of metal under consideration, Thus Pliny referred to Cyprian copper as *aes Cyprium,* the word cuprum not being coined until many years later. Indeed, Spartianus was the first to use it in the third century. When iron was discovered a fresh word was introduced by the Romans, namely ferrum. These observations may be tabulated as follows :

	Sanskrit.		*Latin.*		*Gothic.*	*Greek.*
COPPER OR BRONZE :	ayas	——→	aes	——→	aiz	chalkós
	↓				↓	↓
IRON :	ayas.		[ferrum].		German eisen.	chalkós and [sidēros].

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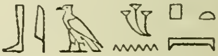
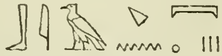
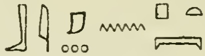
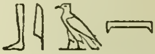
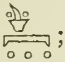
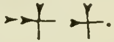
[1] Tylor, "Mexico and the Mexicans," 1861, p. 140.

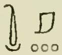
[2] Max Müller, "Lectures on the Science of Language" (Longmans & Co., 1875), vol. ii. p. 253.

[3] *Odyssey,* ix. 391. See Gladstone, "Homer and the Homeric Age," vol. iii. p. 499.

From this it is fairly evident that Sanskrit, Latin, Gothic, and Greek were spoken before iron was known, that is, the Aryan family had broken up prior to the iron age. And upon the discovery of iron either fresh words were invented (words in square brackets in the above scheme) or old ones adapted for its designation.

Egyptologists have long insisted on the importance of the literary evidence in favour of the early knowledge of iron possessed by Egyptians. The word for iron occurs in the early Pyramid texts of Unas ; further, some of the weapons in tomb paintings were painted blue and others red, the former being regarded as referring to iron and the latter to copper or bronze.[1]

Discussing the Egyptian hieroglyphs for iron, Zimmer [2] says : "It is significant that nearly all the ancient folk of culture used in their appellation for iron such words which translate into 'Metal, or something hard, from heaven.' Thus the Egyptians used *ba-en-pet*, variously written  or  or  or  or ; the Assyrians and Babylonians AN.BAR. or *parzillu*, written thus . It is the same in the language of Sumeria and Chaldea—*barsa*, originally *barsal* and *barzel* respectively, and in the Hebrew *barzel*, בַּרְזֶל, all having the same meaning, and it does not require a stretch of imagination that by the name 'Metal of Heaven' they meant meteoric iron.

"It has been suggested that the Egyptian name was comparatively modern and not given to iron till after it had been produced from the ore, simply to signify that such metal sometimes falls as it were from heaven. This argument is undoubtedly strengthened by the fact that the earliest larger piece of iron extant and found in the great pyramid is of terrestrial origin. It must also be admitted that the earliest name in the hieroglyphic for iron was *min*,  At the time when it was so named meteoric iron was no doubt found and used without the users knowing whence it came, and that its name was changed as soon as its origin was discovered into *ba-en-pet,* and as this change did not take place till the Ptolemaic age was nearly reached, we must admit that it took over 2000 years to find this out ; but there is nothing extraordinary in this, when we consider that out of about 300 iron meteorites known to us to-day only about ten have been seen to fall."

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[1] See King and Hall, "Egypt and Western Asia in the Light of Recent Discoveries" (S.P.C.K.), 1907, pp. 112–116.

[2] Zimmer, *Journal of the Iron and Steel Institute*, 1916, No. II. p. 319.

Iron as Treasure.

Various causes contribute to the esteem in which a substance is held by any particular people. They may be purely æsthetic, utilitarian, or a mixture of the two. Thus gold is valued mainly for its beauty and incorrodibility, whilst iron is so useful that it may almost be said to constitute the hub of modern civilisation. Small wonder is it then that, owing to its comparative scarcity, iron should have been regarded in early times as a valuable possession. Possibly the earliest known use of iron for ornamental purposes is its inclusion as beads in a necklace found in a predynastic tomb in Egypt, along with gold and carnelian. This probably dates back some 6000 to 7000 B.C.[1] Mention is made in the sequel of the fact that in the Homeric Age (*circa* 1400 to 1200 B.C.) iron was repeatedly referred to along with the treasures of the wealthy.

It is interesting to note in this connection that iron was used, though probably not extensively, for personal adornment about the time of its introduction into Palestine (*circa* 1000 B.C.). Thus at Gezer various iron objects have been unearthed, including pendants, bracelets, anklets, and rings. In one case the remains of a ring lie " fastened by corrosion to the finger bone, which proves with sufficient clearness that the ring in question is not part of an implement, but a finger ring. The same fact is attested by the various iron signet-rings which have been found." [2]

Speaking of the excavations amongst the ruins of ancient

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[1] See p. 277.

[2] Handcock, " Archæology of the Holy Land " (Unwin, 1916), p. 210. Also see Macalister, " Excavation of Gezer " (3 volumes), published under the auspices of the Palestine Exploration Fund.

Chaldea, Rawlinson[1] states that "Iron . . . is extremely uncommon, and, when it occurs, is chiefly used for the rings and bangles which seem to have been the favourite adornment of the people."

Iron rings have been unearthed on the site of the ancient city of Nimrud in Mesopotamia ; and iron brooches at La Tène in Switzerland (see p. 260), dating back to the third century B.C.

Pliny,[2] in a lengthy discourse on rings, states that at the time of the Second Punic War (218 to 201 B.C.) rings were in very general use. These were mostly of gold, but Pliny is careful to add that "not even in those days did all the senators possess gold rings, seeing that, in the memory of our grandsires, many personages who had even filled the prætorship wore rings of iron to the end of their lives." In Pliny's own day iron was a much more common commodity, and when slaves wore rings of iron they were allowed to encase them with gold. Apparently, however, slaves were not allowed to wear pure gold rings, the use of which was confined to the free.

It is not impossible that the modern use of iron or steel finger rings to "cure" rheumatism is a relic of those times when iron was supposed to ward off attacks of the evil one. The idea that as the iron rusts it draws out the rheumatism is reminiscent of the old cure for toothache, according to which an iron nail is hammered into a tree and as it rusts so will the toothache disappear.

When Julius Cæsar visited these islands he found the Britons in the interior were using iron bars as currency just as in certain parts of Africa, up to the outbreak of the European War in 1914, bars of iron were recognised media of exchange. It is true that coinage was not unknown. There was an old established trade with the continent and coins had been introduced from Gaul some 200 B.C. With these the Southerners would be very familiar.

Many of these currency bars have been discovered in various parts of the south of England. Some of them are heavily corroded, whilst others are in a surprisingly good state of preservation.

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[1] Sir Henry Rawlinson, "Five Great Monarchies," vol. i. pp. 98–99.

[2] Pliny, "Natural History." Translated by Bostock and Riley (Bohn, 1857), Book xxxiii., Chapter 6.

The localities in which the finds have been made are as follows : [1]

LOCALITIES AND NUMBERS OF CURRENCY-BARS FOUND.

Berkshire—
  - Maidenhead (seven or eight in bundle).

Devon—
  - Holne Chase (about twelve specimens).

Dorset—
  - Hod Hill (at least seventeen found).
  - Spettisbury (at least five found).

Gloucestershire—
  - Meon Hill (hoard of 394).
  - Bourton-on-the-Water (two hoards ; numbers given as 147, 140, and 120).

Hampshire—
  - Winchester, Worthy Down (13 bars, 7 perfect).

Isle of Wight—
  - Ventnor (two found together 6 feet deep).

Northants—
  - Hunsbury (one specimen).

Somerset—
  - Wookey Hole (three specimens in fragments).
  - Glastonbury (two of different denominations).
  - Ham Hill or Hamdon (large number found).

Wiltshire—
  - Minety (one specimen).

Worcestershire—
  - Malvern (two hoards of 150 each).
  - Littleton (one specimen, perfect, found in 1822 ; now in Worcester Museum).

The Glastonbury specimens are particularly interesting, having been found " on the site of the marsh village, where there is no trace of contact with Roman civilisation, and the barest evidence of a native British coinage." [2]

In connection with the Hunsbury Hill (Northants) specimen it is interesting to note the entire absence of British coins. This, however, " is not surprising in view of the early La Tène brooches found there, dating from about 400 B.C. ; and the obvious inference is that the iron currency is earlier than the coins in districts where both are found. No currency-bars from the eastern counties, Kent, Surrey, or Sussex have been found, or at least published ; but as those parts of England nearest the Continent were in Cæsar's time ahead of the interior in all branches of civilisation, it is possible that the iron currency was from the first confined to the centre of Southern England, where it was subsequently superseded by the gold coinage introduced from the south-east. But though the British mints no doubt began in the second century before the Christian era, Caesar's mention of the bar-currency (which he probably saw in use) shows that the coinage was not fully established in the interior at the time of his descent on Britain." [1]

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[1] Adapted and brought up to date from the list given by Smith, *Proceedings of the Society of Antiquaries*, 1915, vol. xxvii. p. 69.

[2] Reginald A. Smith, " A Guide to the Antiquities of the Early Iron Age " (British Museum, 1905), p. 149 ; also *Proceedings of the Society of Antiquaries*, 1905, vol. xx. p. 179.

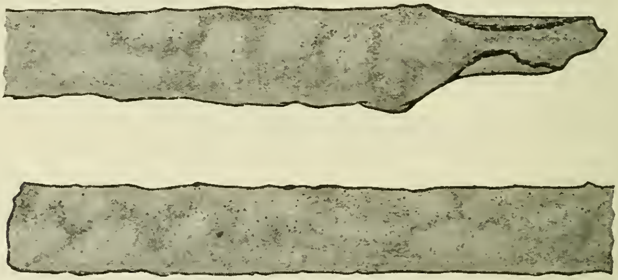

Fig. 1.—Iron Currency Bar. Length, 12·72 inches. Weight, 1933 grains. From a drawing by Mr. W. J. Else, Curator, Worcester Museum.

" The introduction of the use of money into Gloucestershire and the north of Wilts. and Somerset does not appear to have taken place until some time after the days of Julius Caesar." [2]

The bars bear a close resemblance to partly finished swords and consist of a flat, slightly tapering blade with blunt rectangular edges. A rude handle was formed by turning up the edges so as to meet one another at a point 2 inches from one end, as shown in Fig. 1.

Some of these bars may be seen at the British Museum, others

[1] Reginald A. Smith, *Proceedings of the Society of Antiquaries*, 1915, vol. xxvii. p. 69.

[2] Evans, " Coins of the Ancient Britons," p. 41.

at Worcester. It is by no means improbable that yet other currency bars are lying unrecognised in different collections catalogued as unfinished swords or under other names.

The suggestion that these bars were never intended to be swords, but are the actual remains of the currency bars mentioned by Cäesar, was first put forward by Reginald A. Smith, of the British Museum, who offers the following arguments in favour of his theory :

1. Considerable numbers of these bars have been found at times hidden away in the same place. Thus, for example, in 1824 some 394 bars were unearthed from the centre of the British camp at Meon Hill in Gloucestershire, whilst several other hoards have been located at places mentioned in the table on p. 239. It is in the highest degree improbable that the Britons would trouble to bury half-made swords at a crisis ; but they might well be expected to bury their treasure in the hope of recovering it at a later date.

2. The bars are not uniform in size or weight, some bars being as much as sixteen times heavier than others. Only a small percentage of them, therefore, could contain the right amount of metal to yield a sword of the period.

3. The most convincing argument, however, is to be found in the remarkable observation that the weights of the heavier bars must originally have been simple multiples of the weights of the smaller bars.

All the bars as yet described have suffered some loss in weight in consequence of corrosion. Fortunately, however, although some bars have corroded to destruction, others have been found in a relatively good condition, and it is possible to arrive at a rough estimate of their original weight. When this is done, it is found that the weights approximated to 309 grammes (4770 grains), or to some multiple or sub-multiple of this amount. In all, no fewer than six different sizes have been found, of the following presumed standard weights (see table, p. 242).

The third size has been chosen as the unit, namely 4770 grains, owing to the fact that there lies in the Cardiff Museum a bronze weight which was found in association with enamelled bronze ornaments of Late Celtic character near Neath in Glamorganshire. On the top of this weight is engraved the figure I., and it weighs

4770 grains. A similar weight, but in basalt, lies, or rather did lie before the outbreak of the great European war in 1914, in the Mainz Museum. It bears the mark I. and weighs 4767 grains, that is, the same as the preceding within the primitive range of measurement. These weights represent half an Attic commercial mina of the period prior to 160 B.C., and show that even at this early date Britain recognised the same standard weights as the Continent.

Presumed Standard Weights of Currency Bars.

	Grammes.	Grains.	Ounces. Avoirdupois.
Quarter	77	1,193	2¾
Half	154·5	2,385	5½
Unit	309	4,770	11
One and a half	463·5	7,155	16½
Double	618	9,540	22
Quadruple	1236	19,080	44

Yet a third weight has been described, hailing from the province of Namur. It "bore the mark | | | | and weighed '1 kilogramme 25 centigrammes (2½ livres).' An appeal to a well-known almanack puts us in a dilemma. A centigramme being the hundredth part of a gramme, the weight would be 1000·25 grammes = 15,404 grains; but according to the same authority the French pound is 7554 grains, and the alternative weight of the bar is therefore 18,885 grains, that is about 3480 grains or 8 oz. Av. more than 1 kilogramme 25 centigrammes. Scientific accuracy cannot be expected in the division or weighing of rude iron bars, but this margin is anything but a trifle; and the uncertainty is all the more annoying as the weight was evidently four times the unit of a system, and was found with a large amphora, silver denarii, including one apparently of Faustina the elder, pottery, and a brass of Septimius Severus (193–211). The weight was 2·6 in. in diameter, and had been cracked by fire, which probably diminished the weight to some extent. If we suppose centigramme (0·154 grain) a mistake for dekagramme (154 grains), the weight would be 15,400 + 3850 = 19,250 grains, somewhat in excess of 2½ French pounds, but perhaps that was meant only as a rough approximation. The unit in that case would be 4812 grains, against the British unit of 4770 grains."[1]

Two British currency bars were examined by the late Professor Gowland, who reported that one (bar B) was similar in structure to iron produced by primitive methods such, for example, as those adopted in the heart of Africa by the natives at the present time. The other (bar A) resembled meteoric iron, both in analysis (it contained nickel) and in microstructure. This is an observation of particular interest in view of what has been said on pp. 224, 228.

The analyses were as follows[2]:

	Bar A.	Bar B.
Carbon	trace	0·08
Silicon	0·09	0·02
Phosphorus	0·69	0·35
Manganese	nil	nil
Nickel	0·23	nil

More recently the bars found on the site of a prehistoric village on Worthy Down, near Winchester, have been analysed and studied micrographically with interesting results.[3] The chemical analysis was as follows:

	Per Cent.
Carbon (combined)	0·06
Silicon	0·11
Sulphur	0·014
Phosphorus	0·954
Manganese	trace[4]
Nickel	trace

The high phosphorus and low manganese content are noteworthy, the ancient direct-process metal thus differing markedly from modern wrought irons, which are made by indirect methods, and which usually contain[5]:

	Per Cent.
Phosphorus	0·215
Manganese	0·10

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[1] Reginald A. Smith, *loc. cit.*

[2] Quoted by Brough, *Journal of the Iron and Steel Institute*, 1906, No. I. p. 233.

[3] Myers, *Journal of the Society of Chemical Industry*, 1922, vol. xli. p. 133T.

[4] In one specimen manganese was entirely absent.

[5] Means of twelve commercial specimens used in the present author's Research on Corrosion. See this volume, p. 3.

The micrographic structure and the almost entire absence of nickel pointed to the artificial production of the metal. The grains were comparatively coarse and the slag bands relatively broad. Prolonged etching with alcoholic picric acid revealed the presence of elongated aggregates of small foliations which Myers attributes to the "irregular distribution of phosphorus in the solid solution of phosphorus in iron, and the cause, in part, may be due to the movements of both carbon and phosphorus in their respective solid solutions."

In 1918 Stead[1] showed by means of cupric reagents that, where extraneous carbon is introduced into phosphoric iron, phosphorus tends to diffuse away from those areas where the carbon penetrates. Two years later Whiteley[2] found that in the presence of carbon part of the phosphorus contained in γ-iron, between Ac1 and Ac3, diffuses into the adjacent ferrite in which it is more soluble. Now the minute pearlitic areas in the currency bar under examination[3] "clearly show this phosphorus diffusion, and prove that the metal was reheated for some time between 800° and 900° C., followed by fairly rapid air cooling."

It is a wonderful tribute to modern science that it should be possible to determine from purely internal evidence how a primitive worker in pre-Roman times in these islands prepared and heat-treated his metals.

It is difficult to say when bar currency became obsolete in these islands, because different districts varied enormously in their relative states of civilisation. For example, even three centuries after Caesar's first visit there were, an early writer informs us, Britons living in outlying marshy districts, possibly the Cambridgeshire Fens, who "encircled their loins and necks with iron, deeming it an ornament and evidence of opulence, in like manner as other barbarians esteem gold."

The use of bars as a medium of barter dates back to very early times. They were employed by the early Greeks, and Déchelette[4] derived them from the spits used for roasting flesh, a handful being called a *drachm*, in the original sense of that word.

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[1] Stead, *Journal of the Iron and Steel Institute*, 1918, No. I. p. 389.

[2] Whiteley, *ibid.*, 1920, No. I. p. 359.

[3] Myers, *loc. cit.*

[4] Déchelette, *Manuel d'archéologie préhistorique*, vol. ii. Part 2, p. 799; Part 3, p. 1557.

It is said that Pheidon of Argos deposited in the Heraeum certain iron bars that had till his time, namely prior to 600 B.C., done duty as money. Whether these bars had been called in as being obsolete, " or in order to preserve the standard weight or dimensions, has been disputed ; but the fact remains that such a deposit has been discovered there in recent times ; and Déchelette drew attention to a bundle of spits carried by an attendant in the procession represented on the Certosa bucket. They occur also in Etruscan tombs of the eighth to sixth centuries ; and retain their original form in Gaul at least to the end of the fifth century B.C., as specimens were found in the warrior's tomb of Somme Bionne."[1]

It is difficult to understand how the idea of using currency bars reached this country, since none of the peoples between Britain and Greece appear to have adopted the system. Possibly this is but another example of two peoples each independently hitting upon the same idea.

When the Cape of Good Hope was first colonised, the Hottentots were found to be using cattle and bars of iron in place of coins. Similarly on the west coast of Africa the *bar* is, or was prior to the Great European War, the unit of currency, all merchandise being reckoned by it. It had a definite monetary value, although originally it referred to the exchange value of a bar of iron of fixed dimensions, with which the early European traders were accustomed to barter with the natives. In Africa, too, iron has been used very largely by the natives in the interior right down to modern times for purposes of personal adornment. Schweinfurth[2] frequently refers to this in the account of his travels in Central Africa during the years 1868 to 1871. The Bongo and Dyoor tribes loaded themselves heavily with iron rings, &c. Livingstone[3] mentions an interesting case that came under his own personal observation in his travels through the central portion of Southern Africa about the year 1850. The favourite wife of the chief Sheakondo was adorned with a profusion of iron rings on her ankles, to which were attached little pieces of sheet iron to enable her " to make a tinkling as she walked in her mincing African style." Others were ornamented with rings of copper, or a mixed assemblage of copper and iron. Some chiefs were so heavily loaded with these encumbrances that they were forced to strut about with their feet wide apart. This ungainly walk apparently found favour with the younger bloods, who imitated it even when wearing only light rings, and the natives remarked to Livingstone that that was the way in which they showed off their "lordship" in those parts.

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[1] Reginald A. Smith, *loc. cit.*

[2] Schweinfurth, " The Heart of Africa " (Sampson Low), p. 81, *et seq.*

[3] Livingstone, " Missionary Travels " (Ward, Lock), pp. 237, 240, 254.

Schweinfurth[1] stated that the only equivalent for money possessed by the natives in that region was the loggoh kullutty of the Bongo tribe, of which a rough sketch is given in Fig. 2.

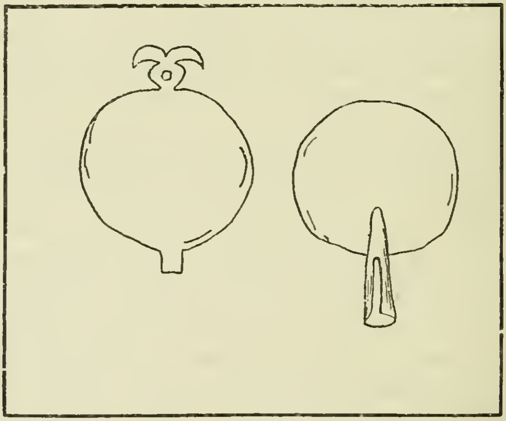

Fig. 2.—Spade-like currency of the Bongo. Left, the Loggoh Kullutty; right, the Loggoh Melot.

It is an iron, spade-like article formed in flat discs from 10 to 12 inches in diameter. On one edge is a short handle, whilst on the diametrically opposite edge is a projecting limb something like an anchor. It is in this form that iron is stored amongst the treasures of the wealthy, and serves in place of money for commercial exchange and for marriage portions. In Cambodia, Indo-China, iron ingots are used as a special kind of money or currency. They are not weighed, but are as long as from the base of the thumb to the tip of the forefinger; they are two fingers in breadth, and one finger thick in the middle, tapering off to either end.

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[1] Schweinfurth, *op. cit.*

Measurements of this kind appear crude to the scientific mind of to-day. But it is well to remember that the *carat*, the standard employed in weighing diamonds, is merely the average weight of the seed of the locust tree, although in more recent years its value has been fixed at 3·1683 grains or 205·310 milligrammes by the Board of Trade in order to reduce the danger of disputes. The French carat is 200 milligrammes. Similarly three barley corns were at one time taken to measure an inch, and the heights of horses are still measured in "hands," a term reminiscent of the time when the span of the average human hand was regarded as a sufficiently accurate standard of measurement.

It is by no means improbable that Christ had treasure of the above kind in mind when He enjoined His followers not to lay up stores on earth "where moth and *rust* doth consume." [1] The same idea of corrosion occurs in connection with gold and silver in the Book of James, where we read that "your gold and your silver are *rusted*; and their *rust* shall be for a testimony against you." [2] But the Greek words translated *rust* in the above passages are not the same in both cases.

IRON IN EUROPE.

It would appear that the Greeks and the Cretans were amongst the first European peoples to use iron. According to Montelius [3] the Grecian iron age commenced about 1400 B.C., but for most of the Keltic and Teutonic peoples the iron age did not commence until about 500 B.C.[4]

Iron and Homer.—Homer, who lived about 880 B.C.,[5] was very familiar with the metal. The Homeric Age, however, as depicted by the *Iliad* and *Odyssey*, is several centuries earlier, being in the main coeval with the Third Late Minoan Period of

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[1] Matt. vi. 19, R.V.

[2] James v. 3, R.V.

[3] Montelius, *Journal of the Iron and Steel Institute*, 1900, No II. p. 514.

[4] Reginald A. Smith, "A Guide to the Antiquities of the Early Iron Age" (British Museum, 1905), p. 1.

[5] Herodotus (*op. cit.*, Book ii., Chapter 53), who was born about 484 B.C., gives it as his opinion that Homer "lived but 400 years before" his time. See also Buckley's Editorial on Pope's translation of the *Odyssey* (Warne & Co.), p. xxiii.

Crete, that is *circa* 1400 to 1200 B.C. The Phæaceans repeatedly referred to in the *Odyssey*[1] appear to be identified with the Minoans of Crete[2] who, at that period, were famous for their sea-power. They lived during the transition period between the bronze and iron ages, and a study of the references to these metals in the poems is full of interest.[3]

Iron, though not regarded as a precious metal in the sense that gold was, ranked amongst the treasures of the wealthy, and is frequently referred to in that sense. Thus, in the *Odyssey* the old wanderer, who is none other than Ulysses himself in disguise, describes to Gumæus the reputed adventures and wealth of Ulysses in distant lands. He says :[4]

> I saw myself the vast un-numbered store
>   Of *steel elaborate* and refulgent ore,
> And brass high heaped amidst the regal dome ;
>   Immense supplies for ages yet to come.

Again, Adrastus at the feet of Atrides begs his life, offering his conqueror stores of iron for ransom :[5]

> Spare me, great son of Atreus ! for my life
>   Accept a price ; my wealthy father's house
> A goodly store contains of brass, and gold,
>   And *well wrought iron* ; and of these he fain
> Would pay a noble ransom, could he hear
>   That in the Grecian ships I yet surviv'd.

Beautiful Penelope, the faithful wife of Ulysses, decides to allow the suitors, who continually press for her favour, to try their strength and bend if possible her hero husband's bow. This she fetches from the treasure-house which contains not only

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[1] *Odyssey*, vi. 266, 270 ; vii. 34, 86–102 ; viii. 247–250, 370–380 ; xiv. 224.

[2] See Drerup, *Homer* (Munich, 1903), pp. 130 *et seq.* ; Burrows, "Discoveries in Crete" (Murray, 1907), p. 208.

[3] It has frequently been urged that the Homeric poems are not the work of a single poet ; the unity of the *Iliad* has, in particular, been made the subject of controversy. In these pages the view is adopted of those scholars who suggest that in the main the poems are the work of one man whom we call Homer, although they are prepared to admit that certain additions and interpolations have been made. See Allen, *Classical Review*, vol. xix. p. 359 ; vol. xx. p. 267 ; vol. xxi. p. 16. Lang, "Homer and His Age" (Longmans, 1906). Ridgeway, "The Early Age of Greece" (Cambridge University Press, 1901). Cotterill, "Ancient Greece" (Harrap, 1913).

[4] *Odyssey*, Pope's translation, xiv.

[5] *Iliad*, Derby's translation, vi.

Ulysses' gold, but bronze and iron. In the words of the poet [1]:

She sought her inmost chamber, the
Recess in which she kept the treasures of her lord,
His brass, his gold, his *steel elaborate.*
Here lay his stubborn bow, and quiver fill'd
With num'rous shafts, a fatal store.

The term "steel elaborate" is, of course, a poetical translation. The metal would be iron as obtained by direct reduction of the ore in small furnaces. Derby's "well wrought iron" in the previous quotation is a very apt translation.

From the foregoing passages it is evident that iron was a well recognised commercial commodity, used just like slaves and cattle for barter as well as for the manufacture of various implements. With regard to the former of these uses, we are told that [2]—

From Lemnos' isle a num'rous fleet had come
Freighted with wine;

and that the—

Greeks
Hasten'd to purchase, some with brass, and some
With *gleaming iron*; other some with hides,
Cattle or slaves; and joyous waxed the feast.

The same idea is further emphasised by the passage in the *Odyssey*,[3] in which Pallas, disguised as Mentes, answers the queries of Telemachus, the son and heir of Ulysses. The goddess says: [3]

With ship and mariners I now arrive,
Seeking a people of another tongue
Athwart the gloomy flood, in quest of brass
For which *I barter steel*, ploughing the waves
To Temesa.

Possibly Temesa is the site of the modern town of Temasus in Cyprus, for this island was the main source of copper in early days—whence the name for copper in modern European languages.[4]

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[1] *Odyssey*, Cowper's translation, xxi. For other examples see *Iliad*, ix., x., xi.

[2] *Iliad*, Derby's translation, vii.

[3] *Odyssey*, Cowper's translation, i.

[4] See p. 235.

In any case, the inference may be drawn that iron was obtainable in sufficiently large quantities to supply ships with cargoes of it. Bearing this in mind, it is remarkable that whilst iron was used in Homeric times for peaceful implements there appears to have been no demand for its use for military purposes. This is well illustrated by the speech of Achilles on the occasion of the funeral feast in honour of Patroclus. It was customary to have trials of strength, and Achilles offered a ponderous lump of iron to him who could hurl it furthest in the contest.[1]

> Next in the ring the son of Peleus plac'd
> A *pond'rous mass of iron*, as a quoit
> Once wielded by Eëtion's giant strength,
> But to the ships with other trophies borne,
> When by Achilles' hand Eëtion fell.
> Then rose, and loudly to the Greeks proclaim'd :
> " Stand forth, whoe'er this contest will essay.
> This prize who wins, though widely may extend
> His fertile fields, for five revolving years
> It will his wants supply ; nor to the town
> For lack of iron, with this mass in store,
> Need he his shepherd or his ploughman send."

At first sight this speech appears remarkably pacific for so redoubtable a warrior as Achilles. One would rather have expected an allusion to the military uses of the metal.[2] As Lang [3] points out, however, " if iron weapons were not in vogue, while iron was the metal for tools and implements, the words of Achilles are appropriate and intelligible." Iron hatchets and axes appear to have been quite usual tools, and Achilles at the above-mentioned funeral games offered ten double-edged axes and ten single hatchets of iron for competition. These do not appear to have been intended for military use. Indeed, it is usually agreed that the Homeric swords, spears, and defensive armour were of bronze,[4] and the Greek word for that alloy is generally employed in the poems. For example, during the fight between

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[1] *Iliad*, Derby's translation, xxiii.
[2] Helbig, *Das homerische Epos*, 1887, p. 330.
[3] Lang, *Revue Archéologique*, 1906, vol. vii. p. 280.
[4] Lang, *loc. cit.* Allen, *Classical Review*, vol. xxi. p. 19. Compare Burrows, *op. cit.*, p. 214, and Ridgeway's reply, *Proceedings of the British Academy*, 1909, vol. iv.

Ulysses and Penelope's suitors, the poet tells us that Telemachus left the hall—

> Seeking the chamber where he had secured
> The armour. Thence he took four shields, eight spears,
> With four fair crested helmets, charged with which
> He hastened to his father's side again,
> And, arming first himself, furnished with arms
> His two attendants. Then *all clad alike*
> *In splendid brass*,[1] beside the dauntless Chief
> Ulysses, his auxiliars firm they stood.[2]

A curious feature of this passage is the fact, that whilst the heroes are distinctly stated to be clad in bronze, Ulysses, in referring to the selfsame weapons,[3] had already implied that they were of *iron* by advising his son to remove them from the hall prior to the fight with the suitors, "since iron of itself attracts a man." Perhaps, however, this is a later interpolation and may have reference to the magnetic property of iron, which was regarded with a certain amount of superstition. The sentence can quite easily be deleted without altering the sense of the narrative.

On the other hand, iron weapons were not altogether unknown at this period. We read of [4]—

> Great Areithous known from shore to shore
> By the huge, knotted *iron mace* he bore.

Again, the arrow used by Pandarus in his stealthy attempt to slay Menelaus at the bidding of Athene bore an iron head.[5]

> At once the sinew and the notch he drew ;
> The sinew to his breast, and to the bow
> The *iron head* ; then, when the mighty bow
> Was to a circle strain'd, sharp rang the horn,
> And loud the sinew twanged, as tow'rd the crowd
> With deadly speed the eager arrow sprang.

The arrow used by Pandarus was very primitive, its head being socketless. It was fastened firmly with sinew and with a tang entering the shaft.[6]

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[1] Better, perhaps, *bronze*.

[2] *Odyssey*, Cowper's translation, xxii.

[3] *Odyssey*, xvi.

[4] *Iliad*, Pope's translation, vii.

[5] *Iliad*, Derby's translation, iv.

[6] Lang, *loc. cit.*

It is of interest to note that on a Mycenæan silver bowl archers are represented as drawing to the breast, in the manner described above.

Iron knives were also known. They were employed, not as weapons of war, but for cutting the throats of victims, as, for example, at a funeral feast.

> There many a steer lay stretched beneath the knife,

we read in connection with the funeral pyre of Patroclus.[1] Bronze knives appear to have been used for this purpose also, however.

One very plausible reason for the continued use of bronze for military weapons in Homeric times is given by Lang,[2] who points out that the early specimens of iron were not always reliable in quality. Owing to imperfect methods of manufacture the metal was liable to bend or buckle. It was thus unsuitable for swords where great strength was required coupled with a minimum thickness. In the case of the mace quoted above a keen cutting edge was not so necessary, the object of the weapon being more particularly to give a stunning blow. Even in this case, however, the mace is spoken of rather as a curiosity than otherwise. Lang's view receives strong, if indirect, support from several other sources. In the account given by Polybius of the Celtic invasion of Italy 223 B.C., reference is made to the poor quality of the iron used by the Celts. The Romans inflicted on them, at the battle of Addua, near Milan, a heavy defeat, attributable mainly to the fact that the long iron swords of the Celts were " easily bent, and would only give one downward cut with any effect, but that after this the edges got so turned and the blades so bent, that, unless they had time to straighten them with the foot against the ground, they could not deliver a second blow." [3] The same kind of difficulty faced the warrior in Iceland more than 1000 years later, as references in the sagas clearly indicate. The " Story of the Ere-dwellers," a famous saga, which deals mainly with the life of Snorri the Priest (A.D. 963 to 1031), affords an apt illustration. The sagas are largely devoted to accounts of family squabbles, and, referring to one of these, the story reads [1]: "So then befell a great battle, and Steinthor was at the head of his own folk, and smote on either hand of him; but the fair-wrought sword bit not whenas it smote armour, and oft he must straighten it under his foot." This was evidently made the subject of joking, for the following year, when engaged in another quarrel, Steinthor drew his sword, and one Thorleif Kimbi called out in derision, "I wot not if thou raisest yet again a soft brand withal, as thou didst last autumn at Swanfirth," to which Steinthor replied lustily, "I will that thou prove ere we part whether I bear a soft brand or not." His sword was of good metal this second time, however, for not only did Steinthor carve off Thorleif's leg neatly at the knee, but cut another man asunder above the hips, without needing to stop and straighten out the metal. Owing to this uncertainty of the quality of the metal, a really good and well-proved iron sword was regarded as an exceptionally valuable weapon, and divine or supernatural powers were frequently attributed to it. Thus we read in the Njal Saga [2] that "Hallgrim has a bill which he had made by seething spells; and this is what the spells say, that no weapon shall give him his death-blow save that bill. That thing follows it too that it is known at once when a man is to be slain with that bill, for something sings in it so loudly that it may be heard a long way off—such a strong nature has that bill in it." This "bill," or battle-axe, was undoubtedly of extra good quality, and became the envy of many. Gunnar, one of the chief characters in the early part of the Njal Saga, and one of the manliest and finest of Icelandic heroes, coveted it exceedingly, his own bill being of but inferior metal. This is well shown by the graphic description of the duel between Gunnar and Hallgrim: "Hallgrim thrust at him with his bill. There was a boom athwart the ship, and Gunnar leapt nimbly back over it. Gunnar's shield was just before the boom, and Hallgrim thrust his bill into it, and through it, and so on into the boom. Gunnar cut at Hallgrim's arm hard and lamed the forearm, but *the sword would not bite.* Then down fell the bill, and Gunnar seized the bill, and thrust Hallgrim through."

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[1] *Iliad*, Derby's translation, xxiii.

[2] Lang, *op. cit.* Also " The World of Homer " (Longmans, 1910).

[3] Polybius, 205 to 123 B.C. Quoted by Ridgeway, " The Early Age of Greece " (Cambridge University Press, 1901), vol. i. p. 408.

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[1] "The Story of the Ere-dwellers," translated by Morris and Magnússon (Quaritch, 1892). The Saga Library, Vol. II.

[2] "The Story of Burnt Njal," translated by Dasent, chapter xxx.

Speaking of the iron made by the natives of Central Africa *circa* 1850, Livingstone[1] said that he had seen a javelin of iron light upon the cranium of a hippopotamus and curl up like the proboscis of a butterfly. In such cases the owner would straighten the metal out again by hammering in the cold between two stones.

Now if the iron familiar to the Homeric heroes was as unreliable as that of the Celts, 223 B.C., or of the Icelanders, A.D. 1000—and the probability is that it was quite as inferior in quality—it is not surprising that bronze weapons should be preferred. For a warrior to be compelled to halt and straighten his sword on the field of battle is surely giving his opponent somewhat of an advantage ![2]

If, on the other hand, Homeric iron was not so poor as described above, it is nevertheless easy to understand that, unless its quality was such as to render it distinctly superior to bronze, the latter metal would be retained by military conservatism, "just as the fifteenth century soldiers found the long-bow and cross-bow much more effective than guns, or as the Duke of Wellington forbade the arming of all our men with rifles instead of muskets."[3] For[4] "soldiers are naturally conservative, and are disinclined to give their confidence to a new weapon or to a new arm of the service till it has proved its worth."

The Greeks in Homeric times appear to have possessed a certain knowledge of tempering. This is hinted at in those lines of the *Odyssey*[5] which portray with graphic effectiveness the blinding of Polyphemus, the one-eyed giant, by Ulysses, who plunged a fiery stake into his orb.

> As when the smith an hatchet or large axe
> Temp'ring with skill, plunges the hissing blade
> Deep in cold water, (whence the strength of steel)
> So hissed his eye around the olive wood.

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[1] Livingstone, "Missionary Travels" (Ward, Lock), p. 557.

[2] Bérard, *Les Pheniciens et l'Odyssée* (Paris, 1902); Lang, *Revue Archéologique*, 1906, vol. vii. p. 280.

[3] Lang, *loc. cit.*

[4] Major-General Maurice, *The Daily Chronicle*, August 10, 1918.

[5] *Odyssey*, Cowper's translation, ix.

The question has frequently been asked whether or not the mass of iron offered by Achilles was of meteoric origin, because it is described in the original Greek as "self smelted." Ridgeway[1] does not consider that it could have been meteoric. "Tempting as this suggestion is," he writes, "we must bear in mind that meteoric stones have in many parts of the world, both ancient and modern, been regarded with awe and veneration. Thus in the Greek lands and those bordering on them, meteoric stones were among the earliest objects of veneration. They were termed *βαίτυλοι*, were usually dedicated to Cronus or to Zeus, and were anointed with oil by devout persons, such as the Superstitious Man in the 'Characters' of Theophrastus. It is not easy to suppose that people who invested meteorites with such sanctity would commit so sacrilegious an act as to use them for metal."

Iron and Herodotus.—There are several allusions to the early use of iron in the "History" of Herodotus written about 450 B.C. According to Eusebius a decree passed the Athenian Assembly in the year 446 B.C., assigning a reward to Herodotus in recognition of his classical work.[2]

The first reference to the metal concerns King Alyattes, who ruled over Lydia, a district in Western Asia Minor, 617 to 560 B.C. After recovering from a serious illness the king sent, as was customary in those days, a handsome present to the temple at Delphi in Phocis, which was famous for the Oracle of Apollo, to which the city of Delphi owed its importance. His present consisted[3] of "a great bowl of pure silver, with a salver in steel curiously inlaid, a work among all the offerings at Delphi the best worth looking at. Glaucus, the Chian, made it, the man who first invented the art of *inlaying* steel." The Greek word *κόλλησις*, here translated *inlaying*, may perhaps really mean *welding*.

A second reference to iron is of particular interest as showing that the Spartans were not acquainted with the working of iron at as early a date as the Tegeans. Thus Lichas is stated to have travelled from Sparta to Tegea.[4] "and, happening to enter into the workshop of a smith, he saw him forging some iron. As he stood marvelling at what he beheld, he was observed by the smith . . ." Herodotus evidently means to imply that the working of iron was a novelty to Lichas. This occurred during the reign of Crœsus, 560 to 546 B.C.—which fixes the date approximately. It is curious that Herodotus should add, a few lines further down, that "iron had been discovered to the hurt of man." The same idea runs through Homer and Virgil, whilst, as will be seen later, Pliny moralises at length in the same strain.

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[1] Ridgeway, "The Early Age of Greece," vol. i., p. 598.

[2] See "The History of Herodotus," translated by Rawlinson (Dent's Everyman's Library, 1916), Introduction, p. xii.

[3] Book i., Chapter 25.

[4] Book i., Chapter 68.

Apparently even at this period iron was regarded with a certain amount of superstitious reverence, for we read[1] that the Phoceans, having voluntarily determined upon exile, "dropped a heavy mass of iron into the sea, swore never to return to Phocæa till that mass reappeared upon the surface." Knowing as they did how readily the metal would corrode under these conditions, they must have regarded their vow as irrevocable. "Nevertheless, as they were preparing to depart for Corsica more than half of their number were seized with such sadness and so great a longing to see once more their city and their ancient homes, that they broke the oath by which they had bound themselves and sailed back to Phocæa."

Several other references by Herodotus to iron in connection with Egypt and the Near East have already been dealt with.

Aristotle,[2] who lived 384 to 322 B.C., and spent much of his life at Athens, states that iron was obtained in large quantities from the ironstone of Elba and from the mines of the Chalybians, near Amisus, on the southern shore of the Black Sea. He states that, in consequence of its high clay content, the ore is difficult to melt. In discussing the metal he says[3]: "Iron is of great strength and very hard, though it is said that in Cyprus there are mice which are able to gnaw it." This statement, however, is probably based on a misunderstanding of a passage by Herodotus,[4] who states that, "as the two armies lay here opposite one another, there came in the night a multitude of field mice, which devoured all the quivers and bowstrings of the enemy, and ate the thongs by which they managed their shields."

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[1] Book i., Chapter 165.

[2] See Lippmann, *Archiv für die Geschichte der Naturwissenschaft und der Technik*, 1910, pp. 233–300; *Stahl und Eisen*, vol. xxx. p. 1099.

[3] See *Journal of the Iron and Steel Institute*, 1910, No. ii. p. 458.

[4] Herodotus, *op. cit.*, Book II., Chapter 141.

Discussing the different varieties of iron known in his day, Aristotle states that " the best and hardest of all the kinds of iron known is that of the Chalybians, that is, steel (Chalybs), and it is obtained from iron by melting it repeatedly together with certain stones in a furnace, during which process much slag is formed and a great loss in weight occurs, on account of which the product is very costly.

" The finished steel is very hard, with a glittering surface, and resists rust ; but it is not applicable to all the purposes for which less pure iron is used. The quality is judged by the sound given out in working it on the anvil."

It is stated that a Sicilian trader, recognising the importance of iron, upon one occasion bought up the entire production from all the smelters and sold again at his own convenience to great profit !

Iron and Crete.—Until close upon the beginning of the present century Crete was regarded as an island of but little interest to the antiquary. Practically nothing was known of its prehistoric cultures, although their existence had been hinted at by some early writers—to wit, Homer, Hesiod, and Thucydides. It remained for the spade of the twentieth-century archæologist to unearth the treasures of bygone ages and to add to the known history of the world yet another chapter which, although as yet imperfect, lacks neither in romance nor in fascinating interest.

The causes leading up to the investigation of ancient remains in Crete emanated from the thrilling discoveries of Schliemann, who, in 1871, began a series of excavations at Hissarlik, the site of ancient Troy. Here he found the remains of several cities, possibly nine, superimposed one above the other, of which the sixth and the second, counting from the bottom upwards, are of special interest. The sixth has since been proved to be the Homeric city of Troy, *circa* 1500 B.C., whilst the second city, dating back to about 2500 B.C., yielded a considerable mass of treasure, including silver vessels and daggers of gold. From Troy Schliemann went to Mycenæ in Greece, where his spade revealed a civilisation evidently contemporaneous with Homeric Troy. In a similar manner other sites disclosed evidences of the same civilisation that had been hidden from the eyes of the curious for ages, and it became clear that this Mycenean culture had at one time spread over a considerable area in that part of Europe and Asia Minor.

Where had this civilisation sprung from? None corresponding to that of the earlier, second city of Troy had been discovered in Greece, and it seemed improbable therefore that the Mycenean civilisation could have resulted purely as the product of the internal growth of that country. Careful search was consequently made for some external source, and in Crete the spade of the archæologist rapidly unfolded to eager eyes evidences of remarkable civilisations in high stages of development which, ages ago, had reached their zenith and passed away into oblivion.

Several different portions of the island have been excavated, but of all the sites Knossos is the most famous, having proved remarkably fruitful under the skilful guidance of Dr. Evans. The low knoll or tell of Knossos consists of successive series of deposits, those of the neolithic or newer stone age beginning at some 17½ feet below the surface and extending to a total depth of about 40 feet. It is believed that these deposits would not form at a greater rate than about one metre in a thousand years, from which it may be gathered that the neolithic settlements at Knossos took place about 10,000 B.C. and continued down to 4000 or 3000 B.C. No traces of paleolithic men have been unearthed, and even the earliest neolithic remains do not indicate the most crude stages of that culture. From this it may be inferred that neolithic man migrated to Crete from some other land, possibly Africa.

Above the neolithic remains lie those of the bronze age and of the later historic Crete. The bronze period has been termed by Evans the *Minoan Age*, in honour of Minos, the legendary sea-king of Crete, mentioned by Homer[1] in the lines—

> One city in extent the rest exceeds,
> Cnossus; the city in which Minos reigned,
> Who, ever at a nine years' close, conferred
> With Jove himself.

Crete was at this time the predominant sea-power of the Mediterranean, and appears to have conquered and laid under tribute the islands of the Ægean Sea.[2] This period extended from about 4000 B.C. to 1200 B.C., during which the civilisation rose to a maximum *circa* 1500 B.C., and continued at its zenith for about fifty years, coeval with the reign of Thothmes III. of Egypt, and then decayed. The close of the Minoan Age came in 1200 B.C., at the time of the Trojan War and the fall of the sixth city of Troy, as depicted by Homer. This was the period of the transition from the bronze age to that of iron in Crete. Thus, at Kavusi on Thunder Hill in Eastern Crete, a short iron sword was found, together with bronze brooches and vases, transitional between Minoan and historic Crete.[1]

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[1] *Odyssey*, Cowper's translation, xix.

[2] Herodotus, Book iii., Chapter 122.

An example of peculiar interest in this connection is afforded by the Muliana Tomb in Eastern Crete.[2] Uncremated bones were found, together with bronze swords and other relics, on one side of the tomb, while later interments were situated on the opposite side, and comprised an iron sword and dagger, as well as cremated bones contained in a cinerary urn resembling in design early Greek vases that have been found at Athens.[3] The interesting feature consists in the fact that the earlier interments had not been plundered or cleared out, as would have been anticipated had they met the eyes of alien intruders. Evans,[4] therefore, concludes that " they had been simply placed on one side in order to make room for the funeral furniture of some later scion of the same family, so that we have here the interesting spectacle of the succession of corpse burial by cremation and of iron weapons by bronze, apparently without any break in the indigenous stock."

Mosso [5] mentions that he excavated beneath the foundations of the Minoan Palace at Phaestos. At a depth of four metres he came across " a piece of magnetic iron weighing half a kilogram. We may suppose that this was a cultus object from the fact that it had never been used as a hammer, though from its shape it might have served for that purpose. I know no more ancient specimen of iron."

Iron in Austria and Switzerland.—Important antiquarian discoveries were made, some years ago, at Hallstatt in the Austrian

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[1] Boyd, *American Journal of Archæology*, 1901, vol. v. p. 128. See also Lang, " The World of Homer " (Longmans, 1910), p. 97.

[2] Described by Xanthoudides, ’Εφ. ’Αρχ., 1904, p. 22.

[3] Burrows, " Discoveries in Crete " (Murray, 1907).

[4] Evans, *Archæologia*, 1905, vol. lix. p. 391; " Prehistoric Tombs of Knossos " (Quaritch, 1906).

[5] Mosso, " The Dawn of Mediterranean Civilisation " (Unwin, 1910).

Tyrol, and at La Tène in Switzerland. The remains were those of the burial places of prehistoric men, those at Hallstatt having reached the transition period from bronze to iron, whilst those at La Tène were somewhat more advanced, and correspond to what is recognised as the Late Celtic age in these islands, and may be regarded as an early iron age. These remains have been studied with exceptional care, and for the sake of convenience have been grouped into various types, known as the Hallstatt and La Tène Periods respectively, representing definite stages of culture in the upward progress of civilisation. With these the antiquities of other countries are compared. This procedure is all the more valuable, inasmuch as different countries could not be expected in byegone ages, any more than now, to reach the same stages of civilisation at the same time. This point has already been emphasised in previous pages (see p. 231).

For Switzerland, France, and Central Europe the following dates have been suggested by various authorities corresponding to the several ages of culture :[1]

Switzerland (Heierli, 1898).	France (Montelius, 1901).	Central Europe (Reinecke, 1902).
Early Hallstatt, 750 to 600 B.C.	Hallstatt I., 850 to 600 B.C.	Hallstatt Periods.
Late Hallstatt, 600 to 400 B.C.	Hallstatt II., 600 to 400 B.C.	La Tène A., Vth Century B.C.
La Tène I., 400 to 200 B.C.	La Tène I., 400 to 250 B.C.	La Tène B., IVth Century B.C.
La Tène II., 200 to 50 B.C.	La Tène II., 250 to 150 B.C.	La Tène C. IIIrd & IInd Century B.C.
La Tène III. and Roman, 50 B.C. onwards.	La Tène III., 150 to 1 B.C.	La Tène D., Ist Century B.C.

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[1] Adapted from R. A. Smith, *op. cit.*, p. xii.

The Hallstatt cemetery is situated in a defile in the Noric Alps of the Austrian Tyrol, hard by the modern village of that name. It has for ages been the scene of extensive salt mining, as its name implies, and lay within forty miles of Noreia, which gave its name to Noricum, one of the earliest centres of the iron industry in Europe. Between 1847 and 1864 excavations were diligently carried out, some 6000 objects being obtained from nearly 1000 graves. Montelius divided the Hallstatt remains into three groups, according to the shape and style of the swords, the Hallstatt I. period being the earliest, and the Hallstatt III. period transitionary to the Early La Tène type. All the evidence goes to prove that in the Hallstatt period there was a gradual growth in culture, bronze being superseded by iron ; it was not a case of the bronze workers being conquered and displaced by workers in iron.

The civilisation of La Tène presents several important contrasts to that of Hallstatt. The site of La Tène lies near Marin in a small bay at the northern end of Lake Neuchâtel in Switzerland. The gradual development of iron brooches is an interesting feature of the finds of La Tène, a ring or collar being developed for keeping the end of the pin in position in a fashion not altogether unlike the end of some modern safety-pins.

Iron in Italy.—There was in Etruria, in Italy, an advanced bronze age culture prior to 1000 B.C., and about this latter date iron swords with bronze handles are common. "From the occurrence of such advanced weapons as swords it might be contended that iron had been in use for several centuries earlier, but this contention will not hold if we remember that the men of the bronze age had already become highly skilled as workers in metal, so that, when once they had obtained a lump of iron from its ore, they would have less difficulty in fashioning it into weapons, especially swords, than they had had with copper or bronze. Hence, from the first discovery of iron until its general use, there would be no long interval of time." [1]

Iron and the Romans.—The Romans were a wonderful people and had developed the metallurgical arts to a remarkably high degree. They made good use of the iron resources of their empire, and reference has already been made to the superiority of their weapons over those of the Celts in the third century B.C. Virgil,[1] the Roman poet, describes the smithy in full work :

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[1] Gowland, "Huxley Memorial Lecture for 1912," Royal Anthropological Institute of Great Britain and Ireland, p. 287.

> A flood of molten silver, brass and gold,
> And deadly steel in the large furnace rolled ;
> Of this, their artful hands a shield prepare,
> Alone sufficient to sustain the war.
> Seven orbs within a spacious round they close,
> One stirs the fire, and one the bellows blows,
> *The hissing steel is in the smithy drowned.*

Clearly the Romans were familiar with steel and the method of tempering it prior to 30 B.C. Study of Pliny's "Natural History" reveals the fact that, at the dawn of the Christian era, the Romans possessed a truly wonderful knowledge of iron, its ores and its metallurgy. Pliny was born about A.D. 23 at Novum Comum, on the southern shore of Lake Larius, in Northern Italy. He died at the age of fifty-six in A.D. 79, falling a victim to his scientific ardour in investigating that fatal eruption of Vesuvius which enveloped Pompeii and Herculaneum in disaster. His book was published two years before his death, namely in A.D. 77.

As a matter of historical interest Pliny states[2] that "the Cyclopes invented the art of working iron." This is but one of the legends common at various times. Pausanias attributes the discovery to Glaucus of Chios ; Strabo to the Idaean Dactyli of Crete, whilst he ascribes the art of manufacturing vessels of iron to the Telchines, who inhabited Rhodes. Breaking away from legend, however, Pliny becomes more informative. After giving a short account of the more common types of ore known to him and the varieties of metal obtainable from them, he passes on to consider the tempering process. Apparently unaware of the influence of the tempering temperature, Pliny[3] ascribes observed differences "to the quality of the water into which the red hot metal is plunged from time to time," and states that "the water, which is in some places better for this purpose than in others, has quite ennobled some localities. . . ." He then makes the following interesting statement, to which the present author has already directed attention elsewhere :[1]

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[1] Virgil, *The Aeneid.* Dryden's translation (Routledge, 1884), Book VIII. The last line has been italicised by the present author. Virgil was born 70 B.C., and was at work on the *Aeneid* when about forty years of age.

[2] Pliny, "Natural History," translated by Bostock and Riley (Bohn, 1857), Book vii., Chapter 57.

[3] Book xxxiv., Chapter 41.

"*It is a remarkable fact, that when the ore is fused, the metal becomes liquefied like water, and afterwards acquires a spongy, brittle texture.*"

This can surely only mean one thing, namely, that the Romans occasionally obtained small quantities of cast iron, possibly by the accidental overheating of their furnaces by extra draught. In that case this passage appears to contain the earliest reference to cast iron in existence. The metal in this condition would be of no use to the Romans, as they possessed no furnaces capable of remelting it for casting purposes. It would therefore either be thrown away or possibly mixed with subsequent charges and passed a second time through the furnace.

Like earlier writers, to whom attention has already been directed, Pliny[2] laments the fatal uses to which iron is put, for "it is with iron also that wars, murders, and robberies are effected, and this, not only hand to hand, but from a distance even, by the aid of missiles and winged weapons, now launched from engines, now hurled by the human arm, and now furnished with feathery wings. This last I regard as the most criminal artifice that has been devised by the human mind ; for, as if to bring death upon man with still greater rapidity, we have given wings to iron and taught it to fly." Strange words these, to fall from the pen of a sturdy Roman admiral.[3]

We are reminded of one of our own generals who, during the late war, described the machine guns used at Gallipoli as inventions of the devil. Military conservatism would appear to be common to all ages.

The pronounced tendency for iron to rust is regarded by Pliny from a very novel point of view. "Nature," he writes,[4] "in conformity with her usual benevolence, has limited the power of iron by inflicting upon it the punishment of rust ; and has thus displayed her usual foresight in rendering nothing in existence more perishable than the substance which brings the greatest dangers upon perishable mortality."

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[1] Friend, *The Foundry Trades Journal*, 1922, vol. xxv. p. 183.

[2] Book xxxiv., Chapter 39.

[3] In A.D. 73 or 74 Pliny had been appointed praefect of the Roman fleet at Misenum, on the western coast of Italy, by Vespasian.

[4] Book xxxiv., Chapter 40.

Again: "Human blood revenges itself upon iron: for if the metal has been once touched by this blood it is much more apt to become rusty."

Pliny also knew that some kinds of iron are less resistant to corrosion than others, and distinctly mentions [1] a species that "is more particularly liable to rust." He further states [2] "that there is in existence at the city of Zeugma, upon the Euphrates, an iron chain by means of which Alexander the Great constructed a bridge across the river, the links of which that have been replaced having been attacked with rust, while the original links are totally exempt from it."

This passage is not only remarkable as being a very early, if not indeed the earliest, statement of the relative corrodibilities of two kinds of iron; it is also of peculiar psychological interest in that it emphasises the unity of human nature throughout the ages. Pliny argues that even in his day the older metal was better than the new. We are involuntarily reminded of the man who complained that *Punch's* jokes are not now as good as they used to be; to which *Punch* pithily replied, "They never were." [3]

This tendency of iron to rust was occasionally turned to good account. Thus Pliny [4] mentions that the "artist Aristonidas, wishing to express the fury of Athamus subsiding into repentance, after he had thrown his son Learchus from the rock, blended copper and iron, in order that the blush of shame might be more exactly expressed, by the rust of the iron making its appearance through the shining substance of the copper; a statue which still [5] exists at Rhodes." It must be admitted that this is a very clever metallurgical conception.

It is interesting to learn that iron, however baneful its nature, may sometimes be put to useful purpose. "For if a circle is traced with iron, or a pointed weapon is carried three times round them, it will preserve both infant and adult from all noxious influences: if nails, too, that have been extracted from a tomb, are driven into the threshold of a door, they will prevent nightmare." [1]

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[1] Book xxxiv., Chapter 41.

[2] Book xxxiv., Chapter 43.

[3] Friend, *Transactions of the Concrete Institute*, 1917–18, vol. ix.

[4] Book xxxiv., Chapter 40.

[5] That is, of course, in Pliny's time.

Superstition with regard to the medicinal value of iron has not even yet entirely disappeared. Mention has already been made of the fact that iron and steel rings are still used as a "cure" for rheumatism.

Apparently as an atonement for its murderous propensities iron, after it has rusted, is stated by Pliny to serve as a remedy in no fewer than fourteen different sicknesses or ailments.[2] "The rust of iron is usually obtained for these purposes by scraping old nails with a piece of moistened iron. It has the effect of uniting wounds, and is possessed of certain desiccative and astringent properties. . . . Diluted in wine, and kneaded with myrrh, it is applied to recent wounds, and, with vinegar, to condylomatous swellings. Employed in the form of a liniment, it alleviates gout."

With regard to the question as to whether the Romans were acquainted with the process of carburising steel by cementation, Stead [3] wrote in 1912 that "it was known that they did manufacture steel, and that it was almost certain that the carbon must have entered the iron by cementation. It was doubtful whether they practised the process as conducted in modern times, but it was easy to conceive how pieces of iron could be carburised by embedding them in the heart of a large charcoal fire and maintaining them at a high temperature by using blast insufficiently strong to penetrate to the centre of the hearth. The combustion of the charcoal near the walls of the furnace in such case would maintain the iron and charcoal at a sufficiently high temperature to admit of any degree of carburisation required."

Further particulars of Roman iron in Europe with analyses and micrographs are given by Neumann.[4]

Iron in Britain.—It is evident that iron was known in Britain at least two centuries before our era, and possibly at an even earlier date. South Wales has been suggested [5] as the early home of the iron trade.

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[1] Book xxxiv., Chapter 44.

[2] Book xxxiv., Chapter 45.

[3] Stead, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 133.

[4] *Zeitschrift für Elektrochemie*, 1923, vol. xxix. p. 175.

[5] Wilkins, "The History of the Iron, Steel, Tinplate and other Trades of Wales," Merthyr Tydvil, 1903.

An account has already been given (see pp. 238, 240) of the iron currency bars which Julius Cæsar found in use amongst the early Britons. After the arrival of the Romans a definite iron industry was established, principally, of course, for military purposes under Roman guidance. In A.D. 120 the Emperor Hadrian founded an Arms factory at Bath, where iron from the Forest of Dean was worked.

An interesting account of a bloom of Roman iron found during excavation work in the old Roman city of Corstopitum was published in 1912.[1] That the bloom was indeed Roman was evidenced from the facts that [2]—

(*a*) It was found amidst purely Roman objects ;
(*b*) No medieval remains had occurred anywhere on the site ; and
(*c*) No iron appears to have been worked in Corbridge, the modern village close to the ancient site, in medieval times.

The site of Corstopitum "lies immediately to the west of the village of Corbridge, on the north bank of the Tyne at the point where a Roman bridge, half a mile west of that now in use, carried Dere or Watling Street across the river." The city, judging from the entire absence of coins after the year 385, appears to have been abandoned about that time. This fixes the lower limit age of the bloom. "The bloom measured 39 inches between the extremities of the metallic portion ; its diameter at the widest part was 7 by 8 inches and at the smallest part 5 by 4½ inches. It weighed 3 cwt. 8 lb., but as it was thickly coated with rust, and contained oxidised slag in the hollow upper part, also much imprisoned slag, it is probable that the net weight of the metallic part was not more than 3 cwt." [3] The bloom showed a decided lack of homogeneity, having been made by building up and welding in sections (see Plate XIII.). It contained a good deal of enclosed slag. At points the metal proved to be "really steel, possibly produced by the carburisation of the spongy iron initially produced when the ore was being reduced in a charcoal fire, and probably the result of accident rather than design. The upper central portion of the bloom was little better than a mixture of iron and cinder, similar in character to a spongy ball of puddled iron. The analysis of the interposed cinder proves that the cinder itself is not a refuse slag, but probably oxide produced by the oxidation of almost pure iron, which might be the result of heating a large number of small pieces of the iron preparatory to welding."

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[1] Sir Hugh Bell, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 118. See also Louis, *ibid.*, p. 120 ; Stead, *ibid.*, p. 121 ; Forster and Knowles, "Corstopitum : Report on the Excavations in 1909" (Reid, Newcastle, 1910).

[2] Haverfield, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 133. See G. Turner, *ibid.*, p. 131.

[3] Stead, *loc. cit.*

Stead gives the average analysis of the bloom as follows:

	Per Cent.
Carbon	0·097
Silicon	0·046
Sulphur	0·025
Phosphorus	0·044
Arsenic	0·049
Copper	0·010
Manganese	0·040
Cinder	0·380

The bloom was undoubtedly made direct from ore, and Louis suggests that it was obtained from the outcrop of local blackbands. He concludes "that the Romans smelted their little balls of iron with charcoal at or near the outcrop of the local ores, and transported the cakes of spongy iron thus produced into the town of Corstopitum to be worked up." Louis states that he has seen similar procedures in India and mentions that the famous Delhi Pillar was probably made in this way.

Iron and the Vikings.—Mention has already been made of the fact that in early Viking days, *circa* A.D. 800 to 1100, the quality of the iron used was liable to vary, so that the swords could not always be relied upon in battle. Gustafson [1] gives an interesting account of the famous Oseberg Ship, which was found in a barrow at Oseberg Ødegaarden, in the parish of Slagen, the ecclesiastical district of Sem in the province of Jarlsberg and Larvik. It was customary in Viking times to bury the dead in a boat or ship which was sunk into the earth and covered with a mound. This particular ship owes its remarkable state of preservation mainly to the fact that it had been buried in clay and covered with peat. It has now been restored and presented to the University Collection of Antiquities at Kristiania. The ship is entirely of oak ; the timbers had become crushed or bent out of shape to a considerable extent, but are so well preserved that it was found possible to steam them back into their original shapes. The beams are riveted together and in the restored boat two-thirds of the rivets are the original metal. "Under the prow is now hung the unusually well-preserved iron anchor, the first anchor of the Viking time that has been found. It appears rather small for the size of the ship. . . . From the ornament and other things, the time of the ship can be fixed at about the year 800. It is thus now 1100 years old."

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[1] Gustafson, "The Oseberg Ship," Kristiania, 1912. Printed by Brogger.

This description fully supports the conclusion already arrived at (see p. 252) that although iron was very useful when employed in relatively thick and heavy pieces, such as bolts and anchors, it was, from imperfections in manufacture, somewhat uncertain when beaten into thin strips for swords.

Iron in India.

There can be no doubt that iron was known in India at a very early date. The metal was certainly worked some 2000 B.C., and from certain passages in the "Black Yajuveda" it would appear[1] that some form of iron cannon or engine of war was in use between 2000 and 1000 B.C. Romesh Chander Dutt records the use of gold, silver, tin, lead, and iron as being well known 1400 to 1000 B.C.[2] Between 500 and 200 B.C. iron appears to have been largely used for military purposes. Probably the most remarkable instance of its employment appears in a medical work, in which nearly 100 surgical instruments are described as used for delicate operations. From certain burial sites in the district of Tinnevelly, iron swords and daggers have been unearthed. They are prehistoric and of uncertain date. Specimens of third century iron have been recovered from Buddha Gaya.

Perhaps the most famous specimen of ancient iron in India is the pillar at Delhi (Plate XIV.), to which, owing to a regrettable series of errors, the date of 912 B.C. has repeatedly been assigned. In reality it only dates back to about A.D. 300. It is 23 feet 8 inches in height, 22 feet being vertically above ground and 20 inches below. Its upper diameter is 12½ inches; its lower 16½ inches; whilst its total weight is approximately 6 tons.[1] According to Miss Gordon Cumming,[2] "it is wrought like our finest metal, and shows no symptoms of rust, though it has stood here for many centuries. It bears an inscription in Sanscrit, describing it as the 'triumphal pillar of Rajah Dhava, A.D. 310, who wrote his immortal fame with his sword.' This, however, is the only record extant of his deeds. There are several other inscriptions on the pillar, but of more modern date.

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[1] Neogi, *Journal of the Royal Society of Arts*, 1914, vol. lxiii. p. 43.

[2] Lester, Presidential Address to the Staffordshire Iron and Steel Institute, September 30, 1911.

"The Brahmin tradition is, that this pillar was erected in the sixth century, after the stars had pointed out the auspicious moment. It went so deep that it pierced the head of the serpent god Schesnag, who supports the earth. The priests told the Rajah that thus his kingdom should endure for ever. But, like a child gardening, he could not be satisfied till he dug it up again, just to see if it were so, and sure enough the end was covered with blood. Then the priests told him that his dynasty would soon pass away. He planted the pillar again, but the serpent eluded his touch, and the pillar was thenceforth unsteady. So the priests called the name of the place Dhilli, that is 'unstable,' and prophesied all manner of evil concerning the Rajah, who shortly afterwards was killed, and his kingdom seized by the Mahommedans, and since then no Hindoo has ever reigned in Delhi.

"Nevertheless, the pillar is now as firm as a rock, and has even resisted the cannon of Nadir Shah, who purposely fired against it. The marks of the cannon balls are clear enough. The Hindoos believe that so long as this column stands, the kingdom has not finally passed from them."

India is a land of legend. A Hindoo judge has informed the writer that there is probably no connection whatever between the name *Delhi*, given to the city of that name, and the word

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[1] Hadfield, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 156; Cunningham, "Archæological Survey of India" (Four Reports made during 1862–1865), Simla, 1871; St. John Vincent Day, *Proceedings of the Philosophical Society of Glasgow*, 1872, vol. viii. No. 2, p. 235; Vincent A. Smith, *Journal of the Royal Asiatic Society*, 1897, p. 11; 1898, p. 143.

[2] Miss Gordon Cumming, "In the Himalayas and on the Indian Plains."

dhili, loose or unstable. The word Delhi more probably means "Heart's Delight."

"This tradition is related in a more poetical form by Kharg Rai," says Cunningham, "who wrote in the reign of Shahjahan. According to him, the Tomar Prince was provided by the sage Vyâs with a golden nail, or spike, 25 fingers in length, which he was told to drive into the ground. At a lucky moment, on the 13th day of the waning moon of Vaisâkh, in the Samvat year 792, or A.D. 736, when the moon was in the mansion of Abhijit, the spike was driven into the ground by the Raja. Then said Vyâs to the king :

Ne'er will thy kingdom be besped,
The spike hath pierced Vasuki's head.

"Vyâs has no sooner departed than the incredulous Raja boldly declared his disbelief in the sage's announcement, when immediately—

He saw the spike thrown on the ground,
Blood-dropping from the serpent's wound.

"The sage was recalled by the horrified king, who was directed to drive the stake into the ground a second time. Again he struck, but the spike penetrated only 19 fingers, and remained loose in the ground. Once more then the sage addressed the Raja prophetically, 'Like the spike (*killi*) which you have driven, your dynasty will be unstable (*dilli*), and after "nineteen" generations it will be supplanted by the Chocans, and they by the Turkans.' "

Cunningham suggests that the long reign of the Tomar dynasty had led to a belief in its permanence which would naturally be compared with the pillar fixed in the ground. A parallel case occurs in Rome, where an old saying, immortalised in verse by Byron, points to a like suggestion :

While stands the Coliseum, Rome shall stand ;
When falls the Coliseum, Rome shall fall.

The pillar is a magnificent tribute to the skill of the early metallurgists of 1600 years ago. It is not a casting but "a huge forging in native Indian or some other Asiatic-made wrought iron."[1] It was built up by welding discs of iron, and it is stated[2] that the marks of welding were a few years ago—and possibly are to-day—plainly to be seen.

A curious feature of the pillar is its remarkable freedom from rust. Hadfield was able to obtain specimens and to submit them to analysis with the following result[3]:

	Per Cent.
Carbon	0·080
Silicon	0·046
Sulphur	0·006
Phosphorus	0·114
Manganese	nil
Total of elements other than iron	0·246
Iron	99·720
Total	99·966

Density, 7·81. Brinell hardness, No. 188

This is probably the first analysis ever made of the pillar. "It will be noticed that the material is an excellent type of wrought iron, the sulphur being particularly low (0·006 per cent.), indicating that the fuel used in its manufacture and treatment must have been very pure (probably charcoal). The phosphorus is 0·114 per cent. There is no manganese present. . . . The iron was ascertained by actual analysis, and not 'by difference.'"[3]

"The high phosphorus and low carbon, sulphur, and manganese contents all tend towards reduction of corrodibility, but do not suffice to explain the general immunity of the pillar from corrosion."[4] This suggests that the resistance to corrosion is due to the surface condition of the metal, which in other similar cases is usually known to be highly polished, and looks as if coated with a fine adherent layer of slag.[5]

Discussing the general freedom of Indian iron from rust, Wallace,[6] writing from Bombay, states: "I have seen native-made iron forged on a stone anvil, and have observed that it does not rust like English iron when exposed to the weather. The ironwork of the car on which the gods of the Kulu Valley take the air has a fine brown patina and no rust flakes. It is all charcoal iron."

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[1] Mallet, quoted by Day, *Proceedings of the Philosophical Society, Glasgow*, December 4, 1872.

[2] See discussion by Turner, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 184.

[3] Hadfield, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 171 (Insertion).

[4] Friend, *Transactions of the Concrete Institute*, 1917–18, vol. ix.

[5] Desch, *Journal of the West of Scotland Iron and Steel Institute*, 1913–14.

[6] John Wallace, *Journal of the Iron and Steel Institute*, 1908, No. I. p. 84.

"Can it be," asks Carulla,[1] "that the stone anvil mentioned by Mr. Wallace siliconides the skin of the Indian iron?" Such an explanation sounds very plausible.

Another iron pillar was erected at Mandu, some twenty-two miles from Dhār, or Dhārā, the ancient capital of Mālava, thirty-three miles west of Indor.[2] It was probably entire in A.D. 1304. "It was thrown down by the Mahommedans and broken into two pieces. After 100 years the larger piece was brought to Dhār, about 1405, when it was erected, but knocked down again and broken into two pieces about 1531."[3] The pillar is thus now in three portions scattered in the town. "The longest portion is 24 feet 3 inches, and is square in section throughout; the second is 11 feet 7 inches, of which 8 feet 6 inches is square and 3 feet 1 inch octagonal; and the third piece, 7 feet 6 inches in length, is of octagonal section except for a circular section at one end, 8 inches deep. The octagonal section is very irregular in form. The total length is 43 feet 4 inches, and the average section is 104¼ inches square. One end of the longest piece, which was originally the base, is slightly bulbous, being 11 to 11¼ inches wide at 2 feet from the end, while the rest measures 10¼ to 10½ inches. Although the length is given as 43 feet 4 inches, it is quite possible from consideration of the proportions and sizes of the octagonal and square portions, that there is a fourth and missing piece, which would bring the total length up to 50 feet."

If these figures are correct, this gigantic column is more than double the height of the Delhi pillar. As Vincent A. Smith says,[4] we marvel at the skill shown by the ancient artificers in forging the great mass of the Delhi pillar, and must give a still greater measure of admiration to the forgotten craftsmen who dealt so successfully in producing the still more ponderous iron mass of the Dhār monument which, like the pillar at Delhi, is of the Gupta period, or about the year 321 of the Christian era. These are the largest masses of ancient iron known to the world, and it is only within comparatively recent years that moderns have learned to deal with masses of iron approaching these in size.

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[1] Carulla, *Journal of the Iron and Steel Institute*, 1908, No. I. p. 85.

[2] See Vincent A. Smith, *Journal of the Royal Asiatic Society*, 1898, p. 143; Graves, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 188; Cousens, *Annual Report of the Archæological Survey of India*, 1902–3. (Issued in 1904 from the Government Press, Calcutta.)

[3] Graves, *loc. cit.*

[4] Vincent A. Smith, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 158.

A fragment of the Dhār Pillar has been analysed by Sir Robert Hadfield,[1] with the following result :

	Per Cent.
Carbon	0·02
Phosphorus	0·28
Iron	99·60

The question has been raised as to whence India derived her knowledge of iron. Babylon is suggested,[2] and it is well established that from very early times iron has been known in what is now Mesopotamia. Others suggest that the Hindoos discovered iron themselves.[3] This is very reasonable. There is, of course, no need to attempt to trace back the discovery of iron to one source. Just as at the present time discoveries are not infrequently made simultaneously in different parts of the world, so it is reasonable to suppose that in early days, when means of communication were slow and primitive, different nations or tribes may have simultaneously unravelled certain of nature's secrets quite independently.

A passing reference to the iron beams from the Black Pagoda at Konarak in the Madras Presidency will suffice, for, although numbers of these heavy beams still lie scattered round the building, in all probability they only date back to the thirteenth century.[4] A detailed description is given by Graves.[5] who states that the temple lies some twenty miles from Puri, which is twelve miles from Calcutta. " Originally the beams were used as supports under the lintels of the doorways and to expedite the corbelling-in of the roof. . . . The Konarak temple has been closed up and filled in with masonry and sand to prevent further falls, so it is not possible to say exactly where the beams were originally placed and whether there are any left *in situ*. Nearly all the beams have been broken by the fall. Some are very heavily rusted, but many are scarcely affected or have a very thin and closely adhering coating. One beam, which is now lying on the portico, has evidently been partially exposed for a long period to the sandy winds, for it is worn down at least an inch in depth, enabling the defective structure to be seen.

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[1] Private communication from Sir Robert Hadfield.

[2] In the case of Northern India. Vincent A. Smith, *loc. cit.*, p. 184.

[3] Notably by J. M. Heath in two papers on Indian steel before the Royal Asiatic Society, 1837, vol. iv. ; 1839, vol. v.

[4] Vincent A. Smith, *loc. cit.*, p. 184 ; Ferguson, " Illustrations of Ancient Architecture in Hindostan " (London, 1848).

[5] Graves, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 187.

" This particular beam and the fractured ends show very clearly that the method of manufacture was by welding up small blooms, generally about 3 or 4 lbs. in weight. The blooms are commonly 2 by 1 inch in section, but occasionally 2 by 2 inches or 1 by 1 inch, and a common length is about 6 inches. . . . Many of the broken ends show the existence of irregular and sometimes uniform cavities. It is possible to thrust a stick down some of them to a depth of 7 or 8 feet, and the sand-blasted specimen shows a cavity nearly the whole length of the beam. From these hollows bits of cinder can be raked out."

Through the kindness of Mr. Graves and of the Secretary of the Iron and Steel Institute, Mr. George C. Lloyd, the present author has been able to test a specimen of metal from Konarak for corrodibility. The metal was cut into a small rectangular block and exposed, along with a similar piece of modern mild steel (carbon, 0·08 per cent.) for one year to the corrosive influence of alternate wet (tap-water) and dry. The relative corrodibilities of the two metals were found to be as follow :

Modern mild steel	100·0
Konarak iron	89·3

The slight superiority of the Konarak metal is very interesting in view of its lack of homogeneity, and further tests are in progress.

Iron in Ceylon.

It is not a far cry from India to Ceylon. " In 543 B.C., Wijiyo and his Sinhalese followers landed in Ceylon, possibly near the modern Puttalam on the west coast. He is said to have been the discarded son of one of the petty princes in the valley of the Ganges, while the native chronicles explain the name of his race by tracing his paternity to a lion—' Sinha.' "[1] During the excavation of some of the ancient buried cities of Ceylon, which date back to the above-mentioned period, and which have had a more or less continuous human history until as late as the sixteenth century, some specimens of ancient iron have been discovered. These number about 250 pieces, and are housed in the Museum at Colombo. Three specimens were submitted to Sir Robert Hadfield for investigation, the results being published[2] in 1912. The details are as follow:

(1) *Chisel from Sigiriya,* of the fifth century A.D. (Plate XV., Fig. 7.)

Length	10 inches.
Density	7·69

Analysis.

Carbon	traces
Silicon	0·12 per cent.
Sulphur	0·003 ,,
Phosphorus	0·28 ,,
Copper[3]	0·090 ,,
Manganese	nil
Iron (estimated direct, not "by difference")	99·3 ,,
Total	99·793

The difference represents slag and oxide.

Micrographic examination led to the conclusion that the chisel had been quenched, the structure being martensitic in parts. Troostite was also detected.

(2) *Nail* (probably also from Sigiriya). (Plate XV., Fig. 8.)

Length	13½ inches
Density	7·69

Analysis.

Carbon	traces
Silicon	0·11 per cent.
Sulphur	nil
Phosphorus	0·32 ,,
Copper	0·119 ,,
Manganese	nil

Micrographic examination revealed slip-bands and showed that the metal had undergone severe hammering. The carbon in the carburised areas existed as granular pearlite.

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[1] S. M. Burrows, "The Buried Cities of Ceylon," 1905.

[2] Hadfield, *Journal of the Iron and Steel Institute,* 1912, No. I. p. 134.

[3] Hadfield, *loc. cit.*, p. 179.

(3) *Native Bill-hook or Ketta.* (Plate XVI., Fig. 9.)

Length	12½ inches
Density	7·50

Analysis.

Carbon	traces
Silicon	0·26 per cent.
Sulphur	0·022 ,,
Phosphorus	0·34 ,,
Copper	0·012 ,,
Manganese	traces

The specimen was very corroded, being covered with thick, brown rust. Micrographic examination showed that it contained a large amount of slag and represents what would now be regarded as a somewhat low grade wrought iron.

The analyses are particularly interesting, because it is comparatively seldom that metallurgists have been able to examine authentic specimens of ancient irons. The carbon is low throughout whilst the phosphorus is high, this latter fact probably serving to account for the high tensile strength of the specimens, which was found to be somewhat higher than for wrought iron. The sulphur is extremely low, showing that a very pure fuel, probably charcoal, had been employed in the production of the metal. The manganese is low, and the copper varies. The presence of troostite in the chisel raises the interesting question as to whether or not the martensite had actually been transformed into troostite by spontaneous annealing during the 1500 years that the specimen had existed.[1] Apropos of this mention might here be made of the ancient Celtic implements obtained during excavations on the site of Steinsburg at Römhild in Thüringen. One weapon or tool, upon micrographic examination,[2] disclosed the presence of ferrite, pearlite, and slag. The point had been hardened and was encased with martensite to a depth of 1 millimetre. Further inwards the structure consisted of martensite and osmondite. The weapon is believed to be some 2000 years old, and whilst it is of interest as showing that the practice of hardening steel was known in Thüringen before the Germans settled there, it also shows, as Hanemann points out, that martensite is very stable in finite time at ordinary temperatures.

[1] Le Chatelier, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 180.

[2] Hanemann, *International Journal of Metallography*, 1913, vol. iv. p. 248.

IRON IN EGYPT.

Iron has been known in Egypt for many thousand years. The dynastic Egyptians were certainly familiar with the metal, but it was not unknown even to the predynastic race. The oxidised remains of iron beads have been discovered in a tomb in a predynastic Egyptian cemetery at El Gerzeh, some forty miles south of Cairo,[1] during excavations under the ægis of the British School of Archæology in Egypt. The string of beads round the neck of the skeleton in the tomb held, in its original order, 3 gold beads, 1 iron, 1 gold, 2 iron, 2 carnelian, 1 gold, 1 iron, 3 agate, 1 gold, 1 carnelian, 1 gold, 1 carnelian, 3 gold. The iron beads were examined by Gowland, who reported that "they consist of hydrated ferric oxide, *i.e.* iron rust, none of the original iron having escaped oxidation. On analysis one gave the following results:

Ferric oxide	78·7	per cent.
Combined water with trace of CO_2 and earthy matter . . .	21·3	,,
	100·0	

"They do not consist of iron ore, but of hydrated ferric oxide, which is the result of the rusting of the wrought iron of which they were originally made."

Similar beads have also been found in other tombs, and it would thus appear established that iron was known to, and prized, by the predynastic Egyptians possibly some 6000 to 7000 B.C.[2]

The problem as to the source of this metal is not easy to solve. It appears in the highest degree improbable that the predynastic race were able to smelt the metal for themselves. Similarly the possibility of their having obtained it by trade from others, such as the negroes, who might have discovered the art, appears equally remote,[3] for in predynastic and early dynastic times the inhabitants of the Upper Nile Valley, as exemplified by the Nubians, were likewise in their chalcolithic stage of civilisation. Their weapons consisted of flint arrows, stone axes, and the like.

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[1] Wainwright, *Revue Archéologique*, 1912, No. I. p. 255.

[2] See Petrie, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 182.

[3] See "Labyrinth and Gerzeh," p. 15 *et seq.*

Even as late as the eighteenth dynasty (*circa* 1600 to 1370 B.C.) the Nubians and negroes never brought iron to Egypt as tribute, though gold, electrum, precious stones, ebony, ivory, bows, arrows, &c., are listed.[1] Nevertheless the Nubians were certainly familiar with the metal at this time. It would almost appear, therefore, that the iron had been found native and, owing to its scarcity, was sufficiently highly prized to rank with gold and carnelian as a precious "stone."

The most ancient piece of dynastic iron yet discovered is that found during blasting operations within the Great Pyramid of Gizeh in 1837. The pyramid was erected in honour of Khufu in the Fourth Dynasty, *circa* 3730 B.C., and the metal cannot be later than this unless, as Petrie points out, it was left there by some later destroyers of the building, which is not impossible.

It was examined by Flight, who concluded that it was not of meteoric origin. Gowland,[2] on the other hand, decided against its being a natural terrestrial product, and suggested that it was "not altogether impossible that it came from the Sinaitic peninsular, and was obtained there by the accidental treatment by the copper smelters of the rich iron ore which crops out near the veins of copper ore."

The Great Pyramid is built of granite blocks from the Upper Nile and lined with Arabian nummulitic limestone. It has frequently been urged that the skill with which these stones have been shaped points to the use of iron tools, as no other material would be sufficiently hard and serviceable. This argument, however, loses force when it is recalled that the early inhabitants of Mexico and of Peru, who were entirely ignorant of iron, were able to cut, shape, and even carve granite and porphyry with the aid of bronze implements and siliceous powder (see p. 288). Whatever uncertainty there may be about the iron found at Gizeh, "an absolutely dated case is that of the mass of rust, apparently from a wedge of iron, found stuck together with copper adzes of the Sixth Dynasty type, at the level of floors of that age in the early temple of Abydos."[3] It was found by Petrie himself. A few other finds of iron have been made, as shown in the accompanying list, but the metal did not come into general use before 1300 to 1200 B.C.[1] The period, therefore, ranging from the earliest use of the metal down to this later date is aptly termed by Petrie the *Sporadic Iron Age*.

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[1] King and Hall, "Egypt and Western Asia in the Light of Recent Discoveries" (S.P.C.K., 1907), pp. 112–116; Hall, *Man*, 1903, vol. iii. p. 147.

[2] Gowland, *loc. cit.*, p. 284.

[3] Petrie, "Ancient Egypt," 1915, Part I. p. 20.

The Sporadic Iron Age of Egypt.

Circa 7000 to 4000[2] B.C.	Predynastic iron beads at El Gerzeh.
3730 B.C. . . .	Iron tool from the Great Pyramid of Khufu at Gizeh. Fourth Dynasty.
3566 B.C. . . .	Fragments of iron picks from the Black Pyramid at Abusir. Fifth Dynasty.[3]
3300–3100 B.C. . .	Mass of iron rust from Abydos. Sixth Dynasty.
2200 B.C. . . .	Iron spear head from Nubia. Thirteenth Dynasty.
1330 B.C. . . .	Iron sickle from beneath a sphinx of Horemheb near Karnak. Eighteenth Dynasty.

From about 1300–1200 B.C. objects of iron become more common. An interesting and very important example is "the iron sword with cartouches of Sety II., 1214–1210 B.C., now in the Berlin Museum. This sword, though much rusted, appears to be of the same type as a more perfect one from Egypt, which is of the European type, of Hungary or the Balkans. It occurs also in Cretan tombs of the age just after the Mycenean and before the geometric style exactly agreeing with our previous dating of the Mycenean age. Now one important point is that this type of sword is more commonly found of bronze than of iron, in Crete and Europe ; hence 1200 B.C. must be about the beginning of the free use of iron ; had it been common before that in Europe such swords would have all been of iron. Also at 1200 B.C. comes the great overthrow of the Libyan invasion, when 9000 bronze swords were taken, showing that iron was not as yet usual. This agrees with the previous, and quite independent, assignment of 1200 B.C. as the date of iron beginning to be used in Crete."[4]

It is, indeed, very remarkable that iron should not have been in general use at a much earlier date. It has been suggested that iron was much better known than we imagine, but that it has oxidised away, leaving little or no trace of its presence. But, as has already been pointed out,[1] the supposition often put forward that iron might entirely disappear in course of time, is a mere fallacy. When buried in earth iron usually corrodes exceedingly slowly. When it has at last been turned to rust, it has become a material which can hardly ever disappear, for oxide of iron is practically insoluble when buried, and its strong colour and staining power make it very obvious.

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[1] Petrie gives the later date. Hall (*Man*, 1903, vol. iii. No. 86) gives the earlier.

[2] Petrie (*Journal of the Iron and Steel Institute*, 1912, No. I. p. 82) gives 6000 to 7000 B.C. The later figure is given by R. A. Smith, "A Guide to the Antiquities of the Bronze Age" (British Museum), 1920, p. 173.

[3] Found by Maspero in 1882.

[4] Petrie, "Ancient Egypt," 1915, Part I. p. 22.

If this is accepted it follows that the relative proportions of ferrous to non-ferrous implements that have been found will give a fair idea of the proportions in which they were made and used, and, as this is so small, Petrie concludes that the sources of iron in the sporadic age were either the native metal or else casual production by accident.

The earliest general group of iron tools in Egypt was found at Thebes. They belonged to the time of the Assyrian invasion of 666 B.C. When magnetised they mostly retained their magnetism, showing they had been hardened to a certain extent.[2]

Iron in Palestine.

Shortly before the Israelites entered Palestine an energetic and cultured race, known in the Bible as the Philistines, had landed there and occupied the fertile regions on the shores of the Mediterranean Sea, *circa* 1200 B.C. They were non-Semitic and appear to have been in some way connected with Crete. The petty skirmishes between the Israelites and the Philistines, frequently alluded to in Holy Writ, are easily understood when it is realised that the Israelites occupied the bleak and barren heights, whilst the Philistines owned the fertile maritime plains below!

It is generally acknowledged that the Philistines introduced the use of iron into Palestine, but it is not improbable that the metal was known many years prior to this. The oldest specimens of iron hitherto found in Palestine are two wedge-shaped lumps found at the bottom of the sloping part of the water-passage at Gezer.[3] The passage had been sealed up prior to 1250 B.C., so that the pieces of metal evidently date back to a time many years anterior to that at which iron came into general use in the country.

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[1] See this Memoir, p. 227.

[2] Petrie, *Journal of the Iron and Steel Institute*, 1912, No. I. p. 182.

[3] Macalister, *Palestine Exploration Fund*, Quarterly Statement, 1908, p. 1.

There are several interesting allusions to iron in Holy Writ, although but few of these are of really early date. Thus we read [1] that Og, King of Bashan, a city of the Amorites, possessed an iron bedstead. The actual dimensions are given, for Og was a giant. "Behold, his bedstead was a bedstead of iron . . . nine cubits was the length thereof, and four cubits the breadth of it, after the cubit of a man." Assuming the cubit to be 20·6 inches, the dimensions of the bed would be 15 by 7 feet. No doubt the word rendered *bed* would have been more correctly translated *bier*, or *sarcophagus*, for beds such as we know them were not then used. That the king should have been laid on a bier was quite a normal occurrence, and probably it would not have been recorded had it not been for the exceptional circumstances that the bier was made of iron.[2]

The great mound of Tel el Hesy, the Lachish of the Old Testament, affords a capital example of the manner in which the debris of successive towns built one upon the other has collected during many centuries in fairly well marked layers, enabling the antiquary to study stage by stage the gradual upward progress of civilisation. In his description of this Gladstone [3] writes: "When Joshua, after the decisive victory of Bethhoron, led his troops to the plain in the south-west corner of Palestine, he besieged and took Lachish,[4] a city of the Amorites. It then became an important stronghold of the Israelites: its vicissitudes are frequently mentioned at various dates of the sacred history, as well as on the Tel el Amarna tablets. . . . In the remains of the Amorite city (perhaps 1500 B.C.) there are large rough weapons of war, made of copper without admixture with tin; above this, dating perhaps from 1250 to 800 B.C., appear bronze tools, with an occasional piece of silver or lead, but the bronze gradually becomes scarcer, its place being taken by iron,[5] till at the top of the mound there is little else than that metal. . . . About 700 B.C., Lachish was the headquarters of Sennacherib, during his invasion of Palestine." The city was finally deserted *circa* 400 B.C.

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[1] Deut. iii. 11, R.V.

[2] See *Encyclopædia Biblica* (Black, MCMI.), vol. i., article "Bed."

[3] J. H. Gladstone, *Nature*, 1898, vol. lvii. 594.

[4] See Joshua x. 31–32.

[5] See Bliss, "A Mound of Many Cities," p. 135.

There was an old Canaanitish legend, to which reference is made in the book of Genesis,[1] in which the humanised god Tubal-Cain is described as "an instructor of every artificer in brass and iron." The word *Tubal* is believed to be Babylonian and connected with *Gibril*, the god of solar fire. The suffix *Cain* is missing from the Greek version and means "artificer." It was probably added to Tubal to explain why the hero was regarded as the father or instructor of smiths.[2] Possibly in the earliest form of the Hebrew legend Tubal was the instructor of men in the art of making fire, probably by rubbing two pieces of wood together, for this is the old Arabian method and appears in later times in connection with ritual. Enoch [3] recalls the general tradition that the first metal worker was a divine being, the fallen angel Azāzel being a teacher of the art.

For centuries the early Hebrews did not use war chariots, although the Canaanites used them largely. Sisera, for example, had 900 of them.[4] The chariots were plated or studded externally with iron after the fashion of the Hittites rather than of the Egyptians.[5] Thus, the children of Joseph said to Joshua: "The Canaanites that dwell in the land of the valley have chariots of iron." [6] Reference is made to the brilliant appearance of these chariots by Nahum,[7] who says: "The chariots shall rage in the streets; . . . they shall seem like torches."

The possession of these chariots evidently gave the Canaanites a great military advantage, for we read [8] that the Israelites "could not drive out the inhabitants of the valley, because they had chariots of iron." An account of the chariots also occurs in the historical inscriptions of Egypt, which are thus independent confirmation. The Canaanites obtained their iron from the mountains of Lebanon,[9] where smelting must have been carried on at a very early date.

David was familiar with iron. In the account of his fight with Goliath, the spear used by that giant is described[1] as having a head weighing 600 shekels of iron. But this was apparently written some 200 years after the event had taken place.[2] In most respects Goliath was armed like the Homeric Heroes.[3] In later years, when collecting material for the temple which his son Solomon was to build, David prepared, amongst other things,[4] "iron in abundance for the nails for the doors of the gates, and for the joinings." Perhaps the most important reference in narratives concerning David occurs in the second book of Samuel,[5] where the writer states that the people of Rabbah were, in accordance with the brutal customs of those times, put "under saws, and under harrows of iron, and under axes of iron." The very fact that the metal is mentioned suggests that bronze weapons were also in use.

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[1] Gen. iv. 22.

[2] See *Encyclopædia Biblica* (Black, MCMI.), vol. i., under "Cainites," section 10.

[3] Enoch viii. 1.

[4] Judges iv. 3.

[5] *Encyclopædia Biblica*, vol. i., under "Chariot."

[6] Joshua xvii. 16.

[7] Nahum ii. 4.

[8] Judges i. 19.

[9] Deut. viii. 9. Jeremiah (xv. 12) speaks of iron from the north.

It is an interesting tradition that no iron was used in the construction of Solomon's temple.[6] We read "that there was neither hammer nor axe nor any tool of iron heard in the house, while it was in building."

This is reminiscent of the habit of using stone knives for ritual, to which practice allusion has already been made (p. 232). To have used metal would have been profane. Solomon appears to have had iron workers of his own, although he had to send to Hiram, King of Tyre, for his foreman or chief worker.[7]

From the time of Amos[8] iron was in general use amongst the Hebrews as well as the Syrians, and smelting furnaces were known to the later Hebrew writers.[9] The comparative values of different metals are instanced by Isaiah[10] in his description of the Zion of the future. "For brass," he says, "I will bring gold, and for iron I will bring silver, and for wood brass, and for stones iron." Steel is not specifically mentioned in the Old Testament.[11]

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[1] 1 Sam. xvii. 7.

[2] *Encyclopædia Biblica* (Black, MCMI.), vol. ii., under "Iron."

[3] Ridgeway, "Journal of Hellenic Studies," 1896, p. 114.

[4] 1 Chron. xxii. 3.

[5] 2 Sam. xii. 31.

[6] 1 Kings vi. 7.

[7] 2 Chron. ii. 7.

[8] See, for example, Amos i. 3; Micah iv. 13; Ezek. iv. 3; Isaiah xlv. 2; Jer. xvii. 1, &c.

[9] See Jer. xi. 4; Deut. iv. 20; 1 Kings viii. 51.

[10] Isaiah lx. 17.

[11] It is incorrect in 2 Sam. xxii. 35; Ps. xviii. 34, 35; Job xx. 24; Jer. xv. 12.

Iron in Mesopotamia.

There can be no doubt that iron was known in the region now called Mesopotamia at a very early date. Indeed, the suggestion has been made (see p. 273) that Northern India derived her knowledge of iron from Babylon.

The Assyrians flourished in Mesopotamia from about 1600 to 625 B.C. According to Ridgeway the earliest reference to iron as occurring in Assyria dates back to 1400 B.C., being contained in the Tel el Amarna tablets, which speak of iron rings covered with gold. On the other hand, "The earliest possible *Assyrian mention* of iron known is by Tiglath Pileser about 1300 B.C. 'Four wild oxen, great and mighty, in the waste land, in the land of Mitauni near by Araziki, which lies before the Hatti-land, I slew with mighty bows Sukuth parzilli.' The last two words are taken to mean 'with arrows of iron' or 'tipped with iron.' It may be that the bows were of iron, but this is very doubtful. The doubt about the passage lies in the fact that parzilli is written ideographically, and its ideogram is the same as that of the god *Ninip*, who was god of war and hunting. Moreover Sukuthe is generally used to denote property, so that a very likely rendering would be 'mighty bows, the property (*i.e.* ideal weapons) of Ninip.' . . . It is therefore quite likely that this is not a case of iron at all." [1]

In making an attack on Mt. Lara in the fourth year of his reign, Ashur-natsir-pal, 885–860 B.C., is stated to have cut a way for his troops with picks of bronze and axes of iron.[2] Tiglath Pileser I. gives a similar account of having to make roads through difficult country. Only bronze picks, however, are mentioned by him. Iron was obtained as tribute from subject cities such as Carchemish. Syria also supplied its toll. Probably iron was first obtained in this way from Armenia by King Sargon.

Ramman-nirari, the Assyrian king, 810–782 B.C., took Damascus during his reign, probably about 797 B.C., and according to inscriptions huge spoil fell into his hands, comprising

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[1] Ridgeway, "The Early Age of Greece" (Cambridge University Press, 1901), vol. i. note, p. 616.

[2] Ridgeway, *op. cit.*, p. 615.

2300 talents of silver, 20 of gold, 3000 of copper, and 5000 of iron, together with large quantities of ivory, &c.[1]

"In support of these records," writes Gowland,[2] "which testify to the extensive use of iron by the Assyrians, we have the remarkable find of Victor Place at Khorsabad. There in the ruins of the palace of Sargon, built about 710 B.C., he found a storehouse containing, according to his estimation, not less than 160,000 kilogrammes of iron.[3] The greater part consisted of iron bars from 12 to 19 inches in length, and $2\frac{3}{4}$ to $5\frac{1}{2}$ inches in thickness. They were roughly drawn out at each end and pierced with a hole (Fig. 3), and weighed from about 8 to 44 lbs. Place supposed them to be work tools of some kind, but they are really bars of iron forged at the furnace of the mines into this shape for convenience of transport by men, horses, or camels.

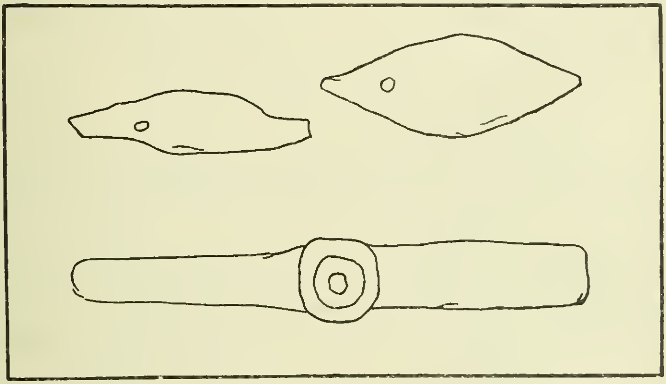

Fig. 3.—Iron found at Khorsabad.

"It is worthy of note here that similar forms survived for iron for transport and trading in Roman times, and even up to thirty or forty years ago in Finland and Sweden.

"The collection was chiefly a store of unworked iron held in readiness by the king for the instruments of war and for building construction. It contained also, however, many kinds of finished iron articles, such as chains, horse-bits, &c., all arranged in regular order.

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[1] See *Encyclopædia Biblica* (Black, MCMI.), vol. ii., art. "Iron."

[2] Gowland, *loc. cit.*, p. 281.

[3] Roughly 150 tons.

"This vast accumulation of iron indicates incontestably that the metal had been in use for many centuries previous to the time of Sargon, so that it will not be unreasonable to assume that the Assyrians were acquainted with iron certainly earlier than 1500 or even 2000 B.C."

Describing the search amongst the ruins in the north-west palace of Nimroud, the ancient Calah, Layard [1] says: "As we approached the floor . . . a large quantity of iron was found amongst the rubbish, and I soon recognised in it the scales of the armour represented on the sculptures. Each scale was separate and of iron, from two to three inches in length, rounded at one end and square at the other, with a raised or embossed line in the centre. The iron was covered with rust. . . . As the earth was removed, other portions of armour were found, some of copper, others of iron, and others of iron inlaid with copper. At length a perfect helmet (representing in shape and in the ornaments the pointed helmet represented in bas-reliefs) was discovered. When first separated from the earth it was perfect, but immediately fell to pieces. . . . The lines which are seen round the lower part of the pointed helmets in the sculptures are thin strips of copper, inlaid in the iron. Several helmets of other shapes, some with the arched crest, were also uncovered, but they fell to pieces as soon as exposed . . . for the iron was in so complete a state of decomposition that it crumbled away on being touched."

Many other metal objects of interest were likewise found. One consisted of an iron ring resting on 3 feet of bronze, which had been cast around the iron. Was the iron used to save the bronze, or was it because it was necessary to the construction? Percy assumes the latter and suggests also that the contrast of iron and bronze may have been regarded as ornamental.[2]

Iron ore is found in the Tiyari Mountains, north-east of Nineveh, and is a source of iron at the present day.[3] It may also have been worked by the Assyrians, although, as mentioned above, iron was largely obtained by them as tribute from subject nations.

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[1] Layard, "Nineveh and its Remains," vol. i. p. 341.

[2] See Layard, "Discoveries in the Ruins of Nineveh and Babylon" (Murray, 1853), Appendix III.

[3] Gowland, *loc. cit.*, p. 281.

IRON IN AFRICA.

The natives of Africa, Egypt excepted, seem to have had no copper or bronze age. They passed directly, like the inhabitants of ancient Spain, into the iron age. Nevertheless, "so far as metallurgical evidence may be relied on, the extraction of iron from its ores was carried on at a very remote date. The seats of an ancient iron industry, marked by accumulations of slags and débris, are so widely distributed in that continent that it must date from a very early period, and, according to Beck,[1] must have been indigenous."[2]

IRON IN CHINA AND JAPAN.

It is difficult to obtain precise information as to how long the Chinese have been familiar with iron; probably they were acquainted with the metal at a period long anterior[3] to that at which it came into common use. The magnetic compass is often said to have been invented by the Chinese earlier than 1000 B.C. If such really was the case, the Chinese must have been acquainted with steel in those days. The province of Shan Si has yielded iron from very remote times.[4]

The bronze age in China is believed[5] to have drawn to a close about 500 B.C. For religious purposes bronze was still the favoured metal, and the art of casting in bronze continued to improve for many centuries, attaining its zenith in the magnificent and gigantic castings of the Northern Wei (A.D. 386–535) and T'ang (A.D. 618–907) dynasties.

In his excavations of the ruined fort of Miran on the borders of Tibet and Chinese Turkestan, Stein[6] found broken shafts of reed arrows and iron arrow-heads. Far more abundant were the relics of defensive armour in the form of lacquered pieces of leather, varying in size, but all oblong, belonging to scale armour. Judging by the way in which the scales had been shed in the different rooms, and by their large number, Stein concludes that armour of lacquered leather must have been worn commonly at the period, namely during the eighth and ninth centuries A.D.

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[1] Beck, *Geschichte des Eisens* (Vieweg).

[2] Gowland, "Huxley Memorial Lecture for 1912," Royal Anthropological Institute of Great Britain and Ireland, p. 285.

[3] Bennett H. Brough (*Journal of the Iron and Steel Institute*, 1906, No. I. p. 233) thinks that iron and steel were known to the Chinese as early as 2357 B.C.

[4] R. A. Smith, "A Guide to the Antiquities of the Bronze Age" (British Museum), 1920, p. 2.

[5] See *Nature*, 1918, vol. cii. p. 250.

[6] M. A. Stein, "Ruins of Desert Cathay" (Macmillan, 1912).

Similarly in his excavations of the Niya site, watered by the river Niya in Chinese Turkestan, Stein[1] found "pieces of a woollen pile carpet, embroidered leather and felt, plaited braids and cords, arrow-heads in bronze and iron, fragments of fine lacquer ware and broken implements in wood and horn."[2]

"Quite at the bottom of the enclosure there turned up a small heap of corn, still in sheaves and in perfect preservation, and close to it the mummified bodies of two mice, which death had overtaken while nibbling at this store."

It would appear, therefore, that whilst iron had already been long known at this date, it had not come into very general use.

Gowland[3] states that "the Japanese when they migrated from the mainland were passing out of the Bronze Age stage of culture and entering the Iron Age, as but few weapons of bronze, only halberds and one or two swords, have been found, and these only in those parts of the islands which were first occupied by them. They had already become skilful workers in iron before they became dolmen builders, three or four centuries B.C. No weapons, except iron swords, spear-heads, and arrow-heads, have been found in the chambers of the dolmens, and all, more particularly the swords, are splendid examples of the work of the smith."

IRON IN MEXICO AND PERU.

It has frequently been urged that the marvellous skill with which the blocks of granite used in the construction of Khufu's pyramid at Gizeh, in Egypt, postulates an early knowledge of iron by the Egyptians. This is not necessarily so, however, for it appears that wonderful carvings have been executed in granite, porphyry, emeralds, and other excessively hard materials by

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[1] Stein, *op. cit.*, p. 275. [2] *Ibid.*, p. 352. [3] Gowland, *loc. cit.*, p. 283.

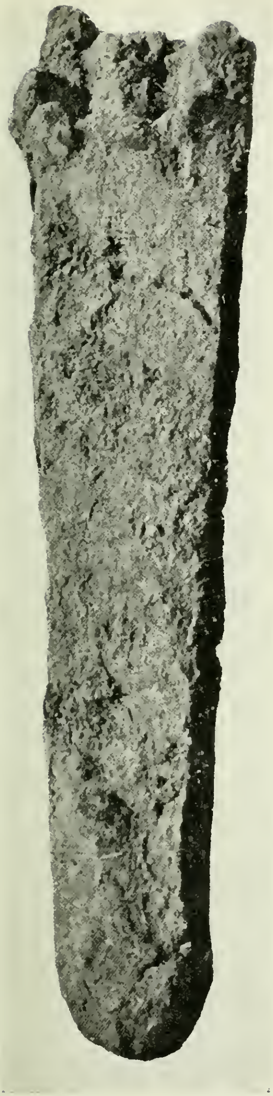

FIG. 4. Bloom of Roman iron found at Corstopitum. Length of metallic portion, freed from rust, 39″, thickness 7″×8″ and 4½″×5″. Weight 3 cwt. 8 lb.

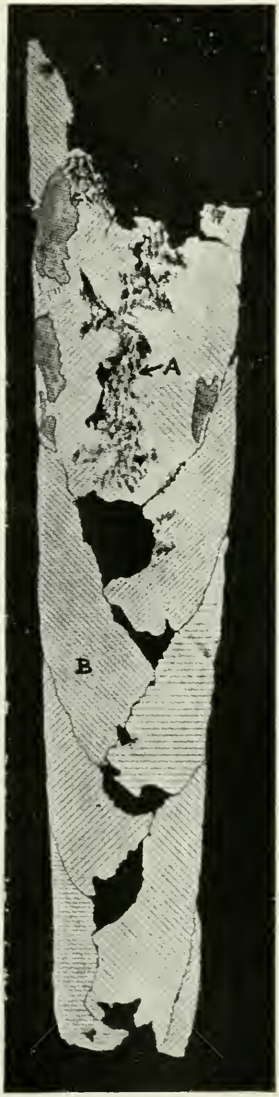

FIG. 5. Photograph of drawing showing how the Roman Bloom was built up (one-seventh natural size).
(J. E. Stead.)

PLATE XIV.

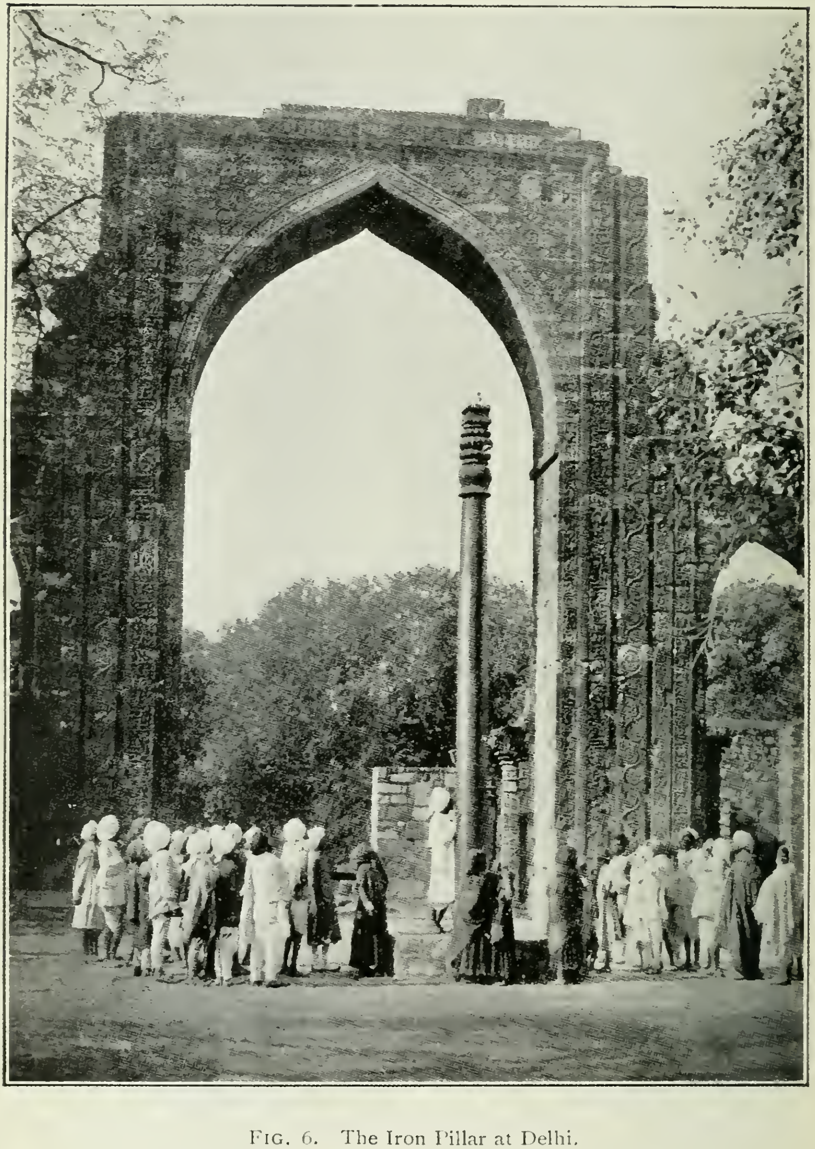

FIG. 6. The Iron Pillar at Delhi.

[*Friend*

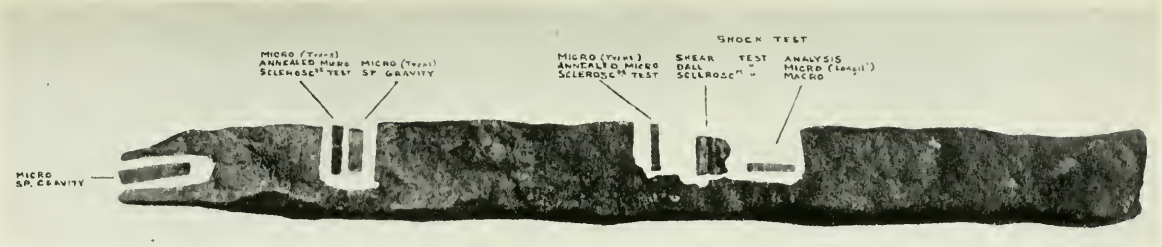
MICRO (Trans.)
ANNEALED MICRO
SCLEROSC^E TEST
MICRO (Trans.)
SP GRAVITY
SHOCK TEST
MICRO (Trans.)
ANNEALED MICRO
SCLEROSC^M TEST
SHEAR TEST
BALL "
SCLEROSC^M "
ANALYSIS
MICRO (Longit.)
MACRO
MICRO
SP. GRAVITY

FIG. 7. Ancient chisel from Sigiriya (5th century A.D.).

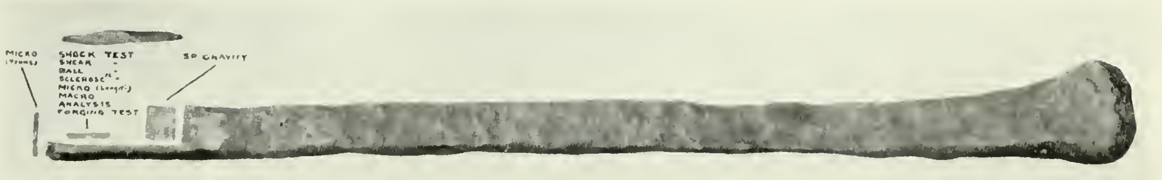
MICRO (Trans.)
SHOCK TEST
SHEAR "
BALL "
SCLEROSC^M "
MICRO (Longit.)
MACRO
ANALYSIS
FORGING TEST
SP GRAVITY

FIG. 8. Ancient nail, 13½″ in length, from Sigiriya (5th century A.D.).

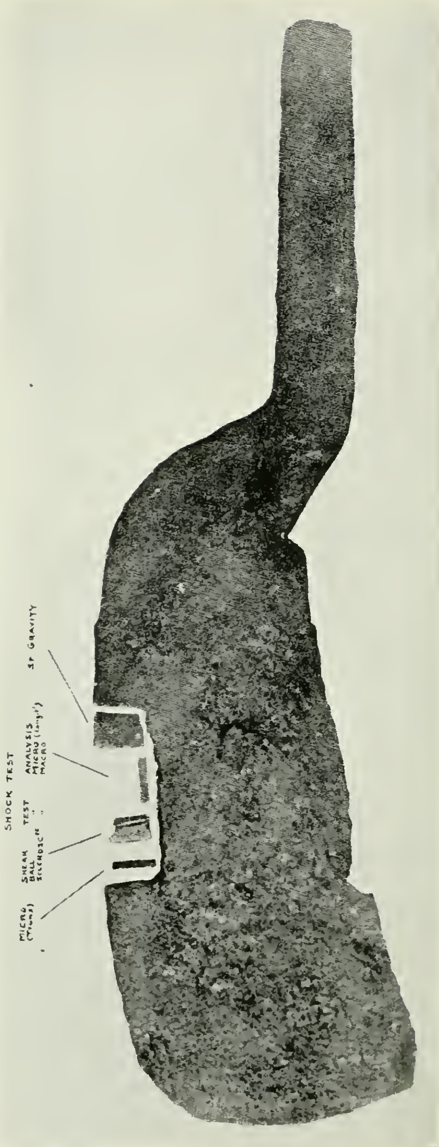
MICRO (trans)
SHEAR
BALL
SCLEROSC^e
SHOCK TEST
TEST
,,
,,
ANALYSIS
MICRO (long^l)
MACRO
SP GRAVITY

FIG. 9. Ancient kellta or billhook.

Mexicans and Peruvians at a time when they were entirely ignorant of iron. Referring to the Peruvians, Prescott says [1]:

"It was comparatively easy to cast and even to sculpture metallic substances, both of which they did with consummate skill. But that they should have shown the like facility in cutting the hardest substances, as emeralds and other precious stones, is not so easy to explain. Emeralds they obtained in considerable quantity from the barren district of Atacames, and this inflexible material seems to have been almost as ductile in the hands of the Peruvian artist as if it had been made of clay. *Yet the natives were unacquainted with the use of iron, though the soil was largely impregnated with it.* The tools used were of stone, or more frequently of copper. But the material on which they relied for the execution of their most difficult tasks was formed by combining a very small proportion of tin with copper. This composition gave a hardness to the metal which seems to have been little inferior to that of steel. With the aid of it, not only did the Peruvian artisan hew into shape porphyry and granite, but by his patient industry accomplished works which the European would not have ventured to undertake. Among the remains of the monuments of Cannar may be seen movable rings in the muzzles of animals, all nicely sculptured of one entire block of granite."

Similarly, in reference to the Mexicans, Prescott says [2]:

"It may seem extraordinary that no iron in the buildings themselves, nor iron tools, should have been discovered, considering that the materials used are chiefly granite, very hard, and carefully hewn and polished. Red copper chisels and axes have been picked up in the midst of large blocks of granite imperfectly cut, with fragments of pillars and architraves, in the quarries near Mitla. Tools of a similar kind have been discovered, also, in the quarries near Thebes; and the difficulty, nay, impossibility, of cutting such masses from the living rock, with any tools that we possess, except iron, has confirmed an ingenious writer in the supposition that this metal must have been employed by the Egyptians, but that its tendency to decomposition, especially in a nitrous soil, has prevented any specimens of it from being preserved.[1] Yet iron has been found, after the lapse of some thousands of years, in the remains of antiquity; and it is certain that the Mexicans, down to the time of the Conquest, used only instruments of copper, with an alloy of tin, and a siliceous powder, to cut the hardest stones, and some of them of enormous dimensions. This fact, with the additional circumstance, that only similar tools have been found in Central America, strengthens the conclusion, that iron was neither known there nor in ancient Egypt."

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[1] Prescott, "The Conquest of Peru," 1847. See Dent's Everyman's Library, 1908, pp. 91–92. The italics are those of the present author.

[2] Prescott, "The Conquest of Mexico," 1843. See Dent's Everyman's Library, p. 394.

FINIS.

It is not suggested that this Memoir gives an exhaustive account of all that is now known of iron in antiquity. An attempt has been made to direct attention to the more important features of the subject, and it is believed that the Memoir contains much information which has not hitherto been collected together under this heading. The author would be glad to receive suggestions and further information from interested readers with a view to expansion at some later date.

In conclusion, the author desires to thank Sir Robert Hadfield for his generosity in giving access to early documents, more particularly in connection with India, and for permission to reproduce Plates XIV., XV., and XVI. To the editor of the *Foundry Trade Journal* the author's thanks are due for permission to reproduce Fig. 1.

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[1] Wilkinson, *Ancient Egyptians*, vol. iii. p. 246.

THE EFFECT OF COLD-WORKING ON THE ELASTIC PROPERTIES OF STEEL.

By J. A. VAN DEN BROEK (The University, Ann Arbor, Mich., U.S.A.).

At the request of Mr. Van Den Broek the following notes in reply to the discussion on his paper are printed here. The original paper was presented at the Annual Meeting, May 2–3, 1918, and published, together with the discussion, in the *Carnegie Scholarship Memoirs,* vol. ix. pp. 125–169.

Mr. Van Den Broek writes as follows : The following points are mentioned by Dr. Rosenhain in his discussion :

First : Accuracy of the measurements.
Second : Interpretation of Bauschinger's data.
Third : Interpretation of Beilby's amorphous cement theory.
Fourth : Questioning conclusions *well* established by others.

First : As to accuracy, Dr. Rosenhain says that my strain gauge measures to 1/10,000 inch. This is a misinterpretation of my statement. On p. 129[1] I say: "The Ames dial registers movements of the end of the lever to 1/10,000 of an inch." Referring to Plate VII., it must be borne in mind that the ratio of the lever arms from the dial to the pivot of the strain gauge and from the pivot to the specimen is 5. Therefore the elongation in 8 inches is measured accurately to 1/5 × 1/10,000 inch. This being the elongation in 8 inches, therefore, the strain, or the elongation per unit length, is measured to an accuracy of $1/8 \times 1/5 \times 1/10{,}000 = 1/400{,}000$ of an inch, which is evidently of a higher accuracy than is obtained with the mirror extensometer to which Dr. Rosenhain refers.

In terms of the diagrams Dr. Rosenhain would seem to intimate that my experimental error in the horizontal direction is as much as 1/5 of a division shown on the diagram, the scale on the diagram being 1 division = 5/10,000 inches per inch. Obviously, my arguments and curves would have been absurd if they were based on data that was unreliable to the extent of 1/5 of a division. Throughout my research I have had confidence in the accuracy of my results, and I still continue to have, in spite of Dr. Rosenhain's remarks. Although only 39 curves were reproduced in the paper, 215 curves were actually obtained, so that I am certain that each curve is truly representative of the class it represents.

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[1] For this and other references, see *Carnegie Scholarship Memoirs,* vol. ix. (1918).

By way of illustration. I want to call attention to curve No. 175 (*m*), Diagram V., p. 162. This curve represents a test on a column 18 inches long, 1 inch square, and tested in compression. This column, without being braced, supported a load of 75,000 lbs. per square inch without buckling. Anyone familiar with column testing will know that by this means I succeeded in obtaining perfect alignment and perfectly uniform bearing at the column's ends. This curve No. 175 (*m*) is, as all curves are, a faithful reproduction of the test data, with the data points exactly located in the centre of the small circles.

A reproduction of the laboratory data sheet for curve No. 175 (*m*) is here offered as a sample illustration.

University of Michigan Physical Testing Laboratory.

History of specimen previous to test:
Material: Low carbon steel.
Original size, 1·0 inch × 1·0 inch.
,, length, 20·40 inches.
Elastic limit, 38,000 lbs. per square inch.
Cold compressed under a maximum load of 86,500 lbs.[1]
Final size, 1·057 inch × 1·057 inch.
,, length, 18·04 inch.

Started boiling, 9.30 A.M.
Finished ,, 10.40 A.M.
Mark 175 (*m*). Date, Nov. 13, 1917.
Kind of test: Compression.
Material: Cold-compressed and boiled mild steel.
Size, 1·057 inch × 1·057 inch.
Area, 1·117 inch.
Length, 18·04 inch.

Load.	Stress.	Gauge.	Strain. Inches per Inch.
0	0	0·0000	0·00000
12,800	11,500	0·0110	0·000275
20,450	18,350	0·0199	0·000498
28,340	25,400	0·0293	0·000733
36,290	32,550	0·0386	0·000965
44,420	39,850	0·0480	0·001200
52,550	47,200	0·0572	0·001430
60,000	53,800	0·0660	0·001650
67,560	60,700	0·0748	0·001870
75,200	67,400	0·0839	0·002099
82,000	73,500	0·0922	0·002305
84,400	75,600	0·0954	0·002385
86,700	77,700	0·0995	0·002487
88,440	79,200	0·1048	0·002620
89,000	79,800	0·1124	0·002810
83,000	75,300	0·1940	0·004850

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[1] The maximum load which the specimen supported after boiling, viz., 89,000 lbs., is only a little more than the load involved in cold-compressing the specimen. If this at first glance appears to be contrary to the conclusions drawn in the text, attention is called to the fact that in cold-working the specimen was braced throughout its length and suffered considerable side pressures. See Plate VIII., *C.S.M.*, vol. ix.

Secondly: Dr. Rosenhain says the author misinterpreted Bauschinger's results. Presumably, since Dr. Rosenhain refused to grant that I have effectively disproved the popular belief that cold-stretching permanently lowers the elastic limit of steel in compression, he wants to continue to accept Bauschinger's work as in support of this belief. To be sure, Bauschinger says:

"As the result of stressing in tension or compression beyond the elastic limit, the elastic limit in compression or tension, respectively, is considerably lowered, so much the more if the cold-working stresses exceed the respective elastic limits by larger amounts, and even comparatively small increments of stress beyond the elastic limits reduce the elastic limit in opposite direction to zero."

It should be noted, however, that Bauschinger also says: "The elastic limit (in tension) is lowered as the result of stretching, often down to zero, so that the specimen, when it is tested immediately after cold-stretching, has no, or else a very much reduced, elastic limit."

Far from disagreeing with either one of these statements of Bauschinger, I have embodied the identical idea of both statements in paragraph 4, p. 148, of my law on "The Effects of Cold Working on the Elastic Properties of Mild Steel," viz., by saying, "When mild steel is cold-worked in any direction or sense and tested in any direction or sense, *without any ageing or tempering*, then the elastic limit falls below the value of the original elastic limit, often down to zero." With reference to tension and compression, this statement of mine may be made to read specifically: When mild steel is cold-worked in tension and tested in compression, without any ageing or tempering, then the elastic limit in compression falls below the value of the original elastic limit, often down to zero.

It would appear that Bauschinger effectively agrees with my contention that the belief in the constancy of an elastic range, namely, that as the result of tensile overstrain the elastic limit in compression is lowered an amount approximately equal to the amount the elastic limit in tension is raised, is a fallacy. It seems to me nothing can be more explicit on that point than his statement: "and even comparatively small increments of stress beyond the elastic limits, reduce the elastic limit in opposite direction to zero."

As to the question whether straining in tension lowers the elastic limit in compression at all or not, I wish to ask how one can persist in discussing this point without duly considering the effect of ageing or tempering at a temperature of boiling water. When it has been shown that ageing or tempering have such tremendous effects, is it not within reason to ask that Dr. Rosenhain give some cognisance to them? If he will read my paper, I think he will find that the only case in which stressing beyond the elastic limit in tension does not lower the elastic limit in compression, is when the specimen is tempered (heated to at least 100° C.) after cold-stretching, and that there is very strong evidence tending to prove that the same results are true when steel is aged after cold-stretching a sufficient length of time, probably a few years.

Third: Dr. Rosenhain would "warn his readers not to accept Mr. Van Den Broek's account of the amorphous theory as representing his (Dr. Rosenhain's) views, or those of his colleagues who had been working on the subject, as it was not a thoroughly satisfactory statement." Indeed, it is cause for regret that my work may not have the recognition of the originator and contributors to this most valuable theory. The amorphous cement theory has its faults as it stands, and I am proud of having contributed towards the elimination of one of the most serious arguments against the validity of this theory. I should like to suggest that it will require something more than a wholesale condemnation of my work by anyone who manifestly has made no effort to study it, to disprove my arguments.

Fourth: Dr. Rosenhain is apparently shocked at my "endeavouring to upset the conclusions *well* established by other workers." Dr. Rosenhain mentions Bairstow's work, but fails to give any explicit reference. I have been familiar with Bairstow's paper on "The Elastic Limits of Iron and Steel under Cyclical Variations of Stress."[1] Instead of contradicting Bairstow's results, I insist that my work is in entire agreement with Bairstow's, so far as the two papers can be compared. It is clear that Bairstow was mainly concerned with cyclical variations, that is, with reversal of stresses before the specimens could be properly aged or tempered after cold straining. What Dr. Rosenhain takes for disagreement, then, again appears to be a lack of appreciation of the time or heat factors on cold-strained steel.

Possibly I am not familiar with other publications by Bairstow to which Dr. Rosenhain refers, in which case I should be very glad of specific references.

In the early history of metallurgy, scientific investigators realised that the subject of greatest interest was the resistance of steel to deformation and rupture. Such men as Bauschinger did very excellent work in studying these phenomena. Subsequently, chemists studied the effect of chemical composition; then came heat treatment and photomicrography, all extremely interesting, but the fact remains they are interesting largely in so far as they bear on the problem of strain and resistance to deformation. In the meantime, the actual phenomena of deformation and elasticity have been sadly neglected. My point of view is that of an engineer and experimenter in a physical laboratory. Rather than apologise for my intrusion into the field so largely held in the past by chemists, I would make a plea for more critical attention being paid by metallurgists to the phenomena of elasticity, stress, and strain.

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[1] *Philosophical Transactions of the Royal Society of London*, Series A, vol. 210, 1911.

Is it not true that there exists a sad difference of opinion as to the exact definition of such terms as elasticity, elastic limit, yield point, &c., and does not such disagreement argue a certain vagueness and lack of understanding of such problems ?

I regret that one serious error in the paper was allowed to go uncorrected. On the original curves, tangents were drawn in to mark clearly the point of elastic limit. These tangents were not reproduced in the diagrams as published. These would have been of considerable help in interpreting the curves. It would be obvious, for example, in Diagram IV., that the elastic limit on curve No. 118 (*t*) is 35,000 lbs. per square inch ; on curve No. 114 (*t*) it is 0 lb. per square inch ; on curve No. 115 (*t*) it is 22,000 lbs. per square inch ; on curve No. 112 (*t*) it is 35,000 lbs. per square inch again ; and on curve No. 171 (*p*) it is 26,000 lbs. per square inch.

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